MiniBooNE Anomaly and Nuclear physics

PRL121(2018)221801

outline

1. MiniBooNE neutrino experiment
2. Nucleon correlations
3. Pion puzzle
4. NC single photon production
5. Conclusions

Teppei Katori
Queen Mary University of London
ECT* workshop, Trento, Italy, April 15, 2019

1. MiniBooNE neutrino experiment

2. Nucleon correlations

3. Pion puzzle

4. NC single photon production

5. Discussions

BackReAction

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Thursday, May 31, 2018

New results confirm old anomaly in neutrino data

The collaboration of a neutrino experiment called MiniBooNe just published their new result

> **Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment**
> MiniBooNE Collaboration
> arXiv:1805.12028 [hep-ex]

It's a rather unassuming paper, but it deserves a signal boost because for once we have an anomaly that did not vanish with further examination. Indeed, it actually increased in significance, now standing at a whopping 6.1σ.

GIZMODO

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PHYSICS

Physicists Are Excited About Fresh Evidence for a New 'Sterile' Fundamental Particle

Ryan F. Mandelbaum
6/04/18 3:20pm • Filed to: NEUTRINOS

19.4K 5 9

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Science & Environment

Has US physics lab found a new particle?

By Paul Rincon
Science editor, BBC News website

6 June 2018

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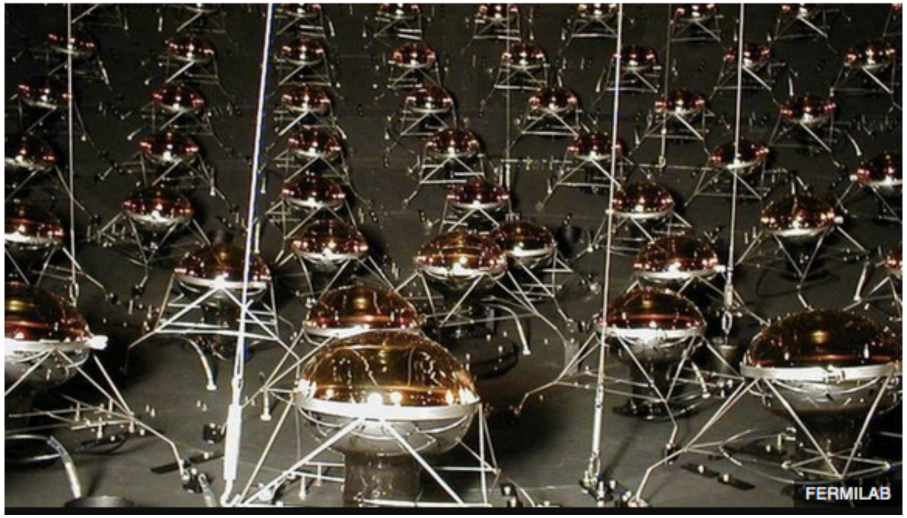
ABSTRACTIONS BLOG

Evidence Found for a New Fundamental Particle

10

An experiment at the Fermi National Accelerator Chicago has detected far more electron neutrino a possible harbinger of a revolutionary new elen called the sterile neutrino, though many physicis



PHYSICAL REVIEW LETTERS

Significant Excess of Electronlike Events in the MiniBooNE Short-Baseline Neutrino Experiment

A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration)
Phys. Rev. Lett. **121**, 221801 – Published 26 November 2018

Physics See Viewpoint: The Plot Thickens for a Fourth Neutrino

The most visible particle physics result of the year

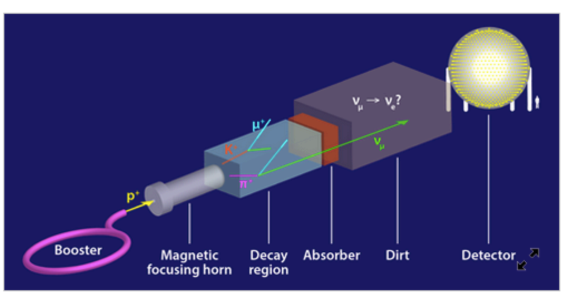
ALL RESEARCH OUTPUTS	OUTPUTS FROM PHYSICAL REVIEW LETTERS	OUTPUTS OF SIMILAR AGE	OUTPUTS OF SIMILAR AGE FROM PHYSICAL REVIEW LETTERS
#7,064 of 12,363,617 outputs	#13 of 25,606 outputs	#448 of 270,805 outputs	#1 of 520 outputs

Viewpoint: The Plot Thickens for a Fourth Neutrino

Joachim Kopp, Theoretical Physics Department, CERN, Geneva, Switzerland, and PRISMA Cluster of Excellence, Mainz, Germany

November 26, 2018 • *Physics* 11, 122

Confirming previous controversial results, the MiniBooNE experiment detects a signal that is incompatible with neutrino oscillations involving just the three known flavors of neutrinos.



APS/Alan Stonebraker

https://physics.aps.org/articles/v11/122

PHYSICAL REVIEW LETTERS

Observation of $t\bar{t}H$ Production

A. M. Sirunyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **120**, 231801 – Published 4 June 2018

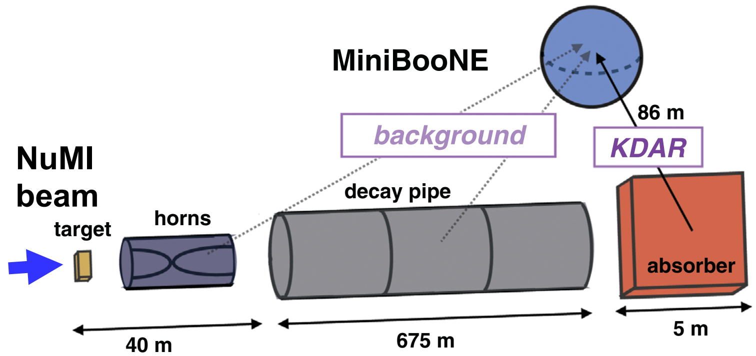
Physics See Viewpoint: Sizing Up the Top Quark's Interaction with the Higgs

PHYSICAL REVIEW LETTERS

Observation of Higgs Boson Decay to Bottom Quarks

A. M. Sirunyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **121**, 121801 – Published 17 September 2018

Physics See Viewpoint: Higgs Decay into Bottom Quarks Seen at Last

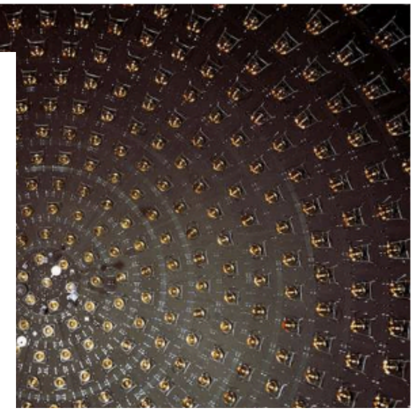


PHYS ORG
Nanotechnology Physics Earth Astronomy & Space Technology Chemistry Biology

Home » Physics » General Physics » June 5, 2018

Blast from the past—First measurement of mono-energetic neutrinos

June 5, 2018 by Savannah Mitchem, Argonne National Laboratory



PHYSICAL REVIEW LETTERS **120**, 141802 (2018)

Editors' Suggestion Featured in Physics

First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions

A. A. Aguilar-Arevalo,[13] B. C. Brown,[6] L. Bugel,[12] G. Cheng,[5] E. D. Church,[20] J. M. Conrad,[12] R. L. Cooper,[10,16] R. Dharmapalan,[1] Z. Djurcic,[2] D. A. Finley,[6] R. S. Fitzpatrick,[14,*] R. Ford,[6] F. G. Garcia,[6] G. T. Garvey,[10] J. Grange,[2,†] W. Huelsnitz,[10] C. Ignarra,[12] R. Imlay,[11] R. A. Johnson,[3] J. R. Jordan,[14,‡] G. Karagiorgi,[5] T. Katori,[17] T. Kobilarcik,[6] W. C. Louis,[10] K. Mahn,[5,15] C. Mariani,[19] W. Marsh,[6] G. B. Mills,[10] J. Mirabal,[10] C. D. Moore,[6] J. Mousseau,[14] P. Nienaber,[18] B. Osmanov,[7] Z. Pavlovic,[10] D. Perevalov,[6] H. Ray,[7] B. P. Roe,[14] A. D. Russell,[6] M. H. Shaevitz,[5] J. Spitz,[14,§] I. Stancu,[1] R. Tayloe,[9] R. T. Thornton,[10] R. G. Van de Water,[10] M. O. Wascko,[8] D. H. White,[10] D. A. Wickremasinghe,[3] G. P. Zeller,[6] and E. D. Zimmerman[4]

(MiniBooNE Collaboration)

PRL120(2018)141802

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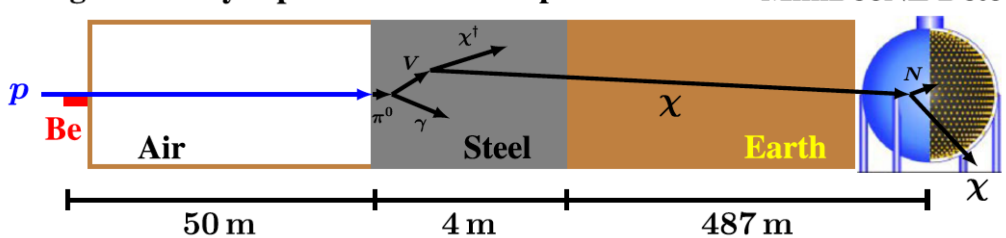
News at work



MiniBooNE keep providing high impact results!

PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

Dark Matter Search in a Proton Beam Dump with MiniBooNE

A. A. Aguilar-Arevalo,[1] M. Backfish,[2] A. Bashyal,[3] B. Batell,[4] B. C. Brown,[2] R. Carr,[5] A. Chatterjee,[3] R. L. Cooper,[6,7] P. deNiverville,[8] R. Dharmapalan,[9] Z. Djurcic,[9] R. Ford,[2] F. G. Garcia,[2] G. T. Garvey,[10] J. Grange,[9,11] J. A. Green,[10] W. Huelsnitz,[10] I. L. de Icaza Astiz,[1] G. Karagiorgi,[5] T. Katori,[12] W. Ketchum,[10] T. Kobilarcik,[2] Q. Liu,[10] W. C. Louis,[10] W. Marsh,[2] C. D. Moore,[2] G. B. Mills,[10] J. Mirabal,[10] P. Nienaber,[13] Z. Pavlovic,[10] D. Perevalov,[2] H. Ray,[11] B. P. Roe,[14] M. H. Shaevitz,[5] S. Shahsavarani,[3] I. Stancu,[15] R. Tayloe,[6] C. Taylor,[10] R. T. Thornton,[6] R. Van de Water,[10] W. Wester,[2] D. H. White,[10] and J. Yu[3]

MiniBooNE-DM Collaboration

PRL118(2017)221803
PRD98(2018)112004

Queen Mary University of London

1. LSND experiment

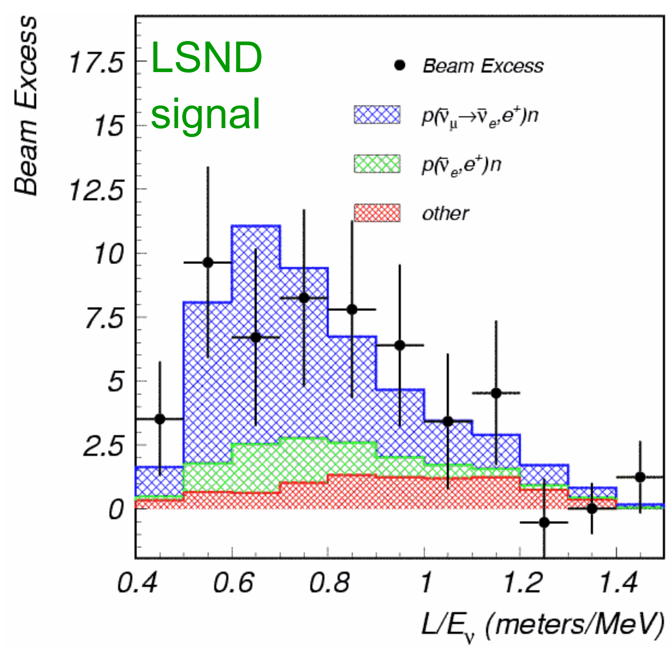
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

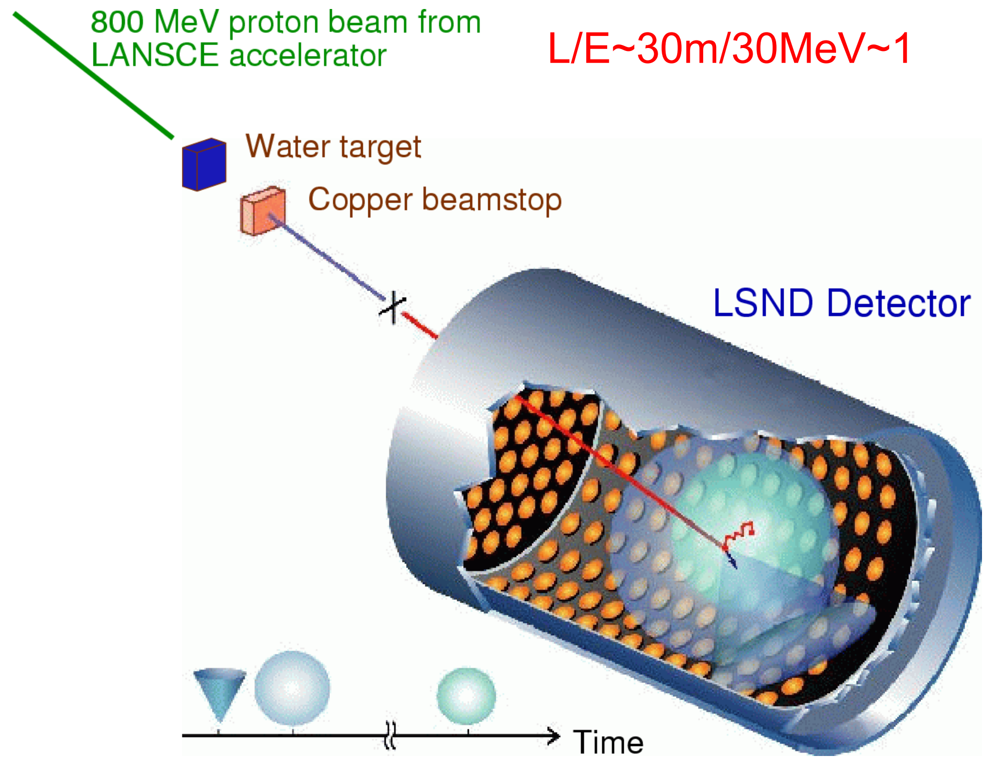
LSND experiment at Los Alamos observed excess of anti-electron neutrino events in the anti-muon neutrino beam.

$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \to e^+ + n$$

$$n + p \to d + \gamma$$

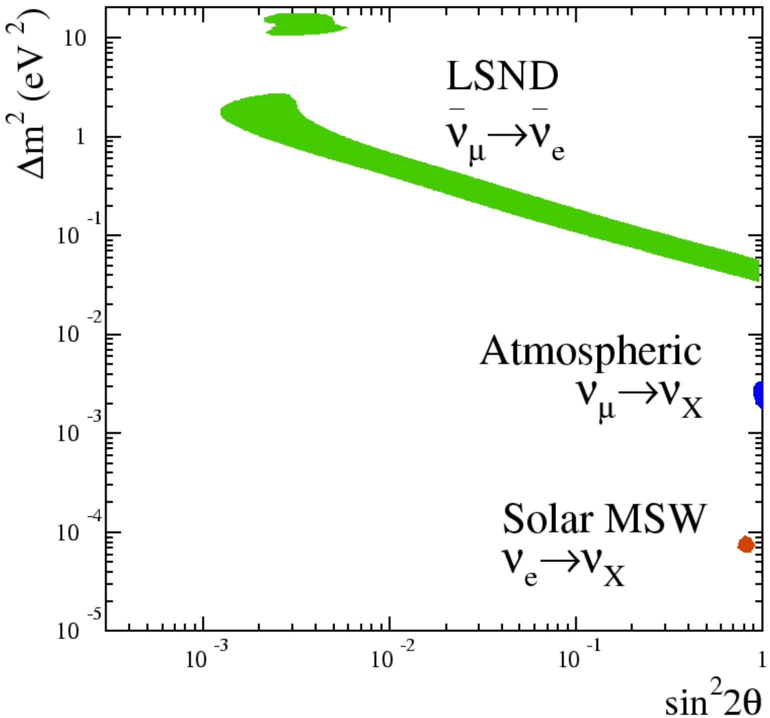
87.9 ± 22.4 ± 6.0 (3.8.σ)





L/E~30m/30MeV~1

1. LSND experiment

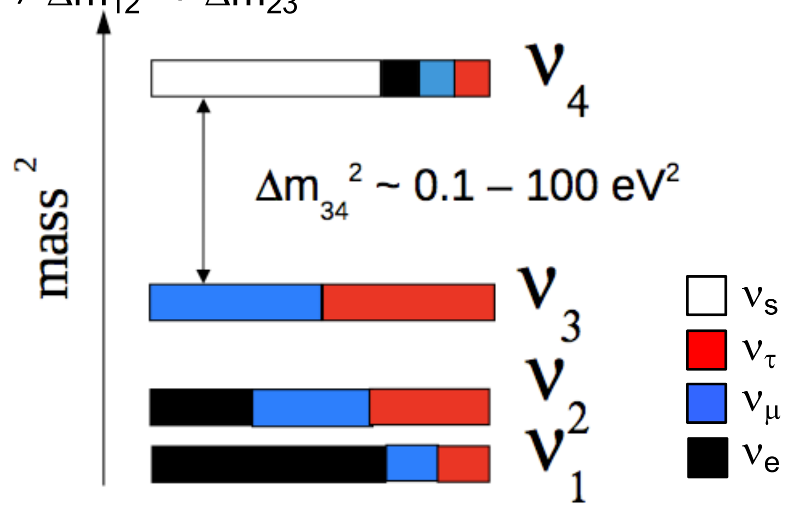


3 types of neutrino oscillations are found:

LSND neutrino oscillation: $\Delta m^2 \sim 1 eV^2$
Atmospheric neutrino oscillation: $\Delta m^2 \sim 10\text{-}3 eV^2$
Solar neutrino oscillation : $\Delta m^2 \sim 10\text{-}5 eV^2$

But we cannot have so many Δm^2!

$\Delta m_{13}^2 \neq \Delta m_{12}^2 + \Delta m_{23}^2$



LSND signal indicates 4th generation neutrino, but we know there is no additional flavour from Z-boson decay, so it must be sterile neutrino
MiniBooNE is designed to have same L/E~500m/500MeV~1 to test LSND $\Delta m^2 \sim 1 eV^2$

1. MiniBooNE experiment

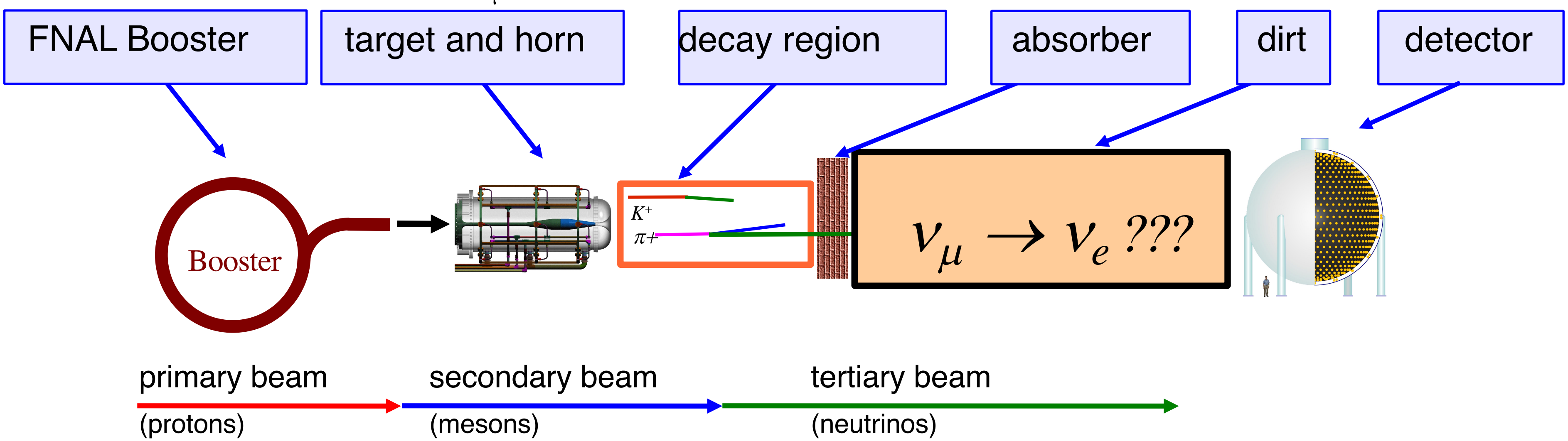
$$P(\nu_\mu \to \nu_e) = sin^2 2\theta sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

Keep L/E same with LSND, while changing systematics, energy & event signature;

MiniBooNE is looking for the single isolated electron like events, which is the signature of ν_e events

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \to p + e^-$$

$$\bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e + p \to n + e^+$$

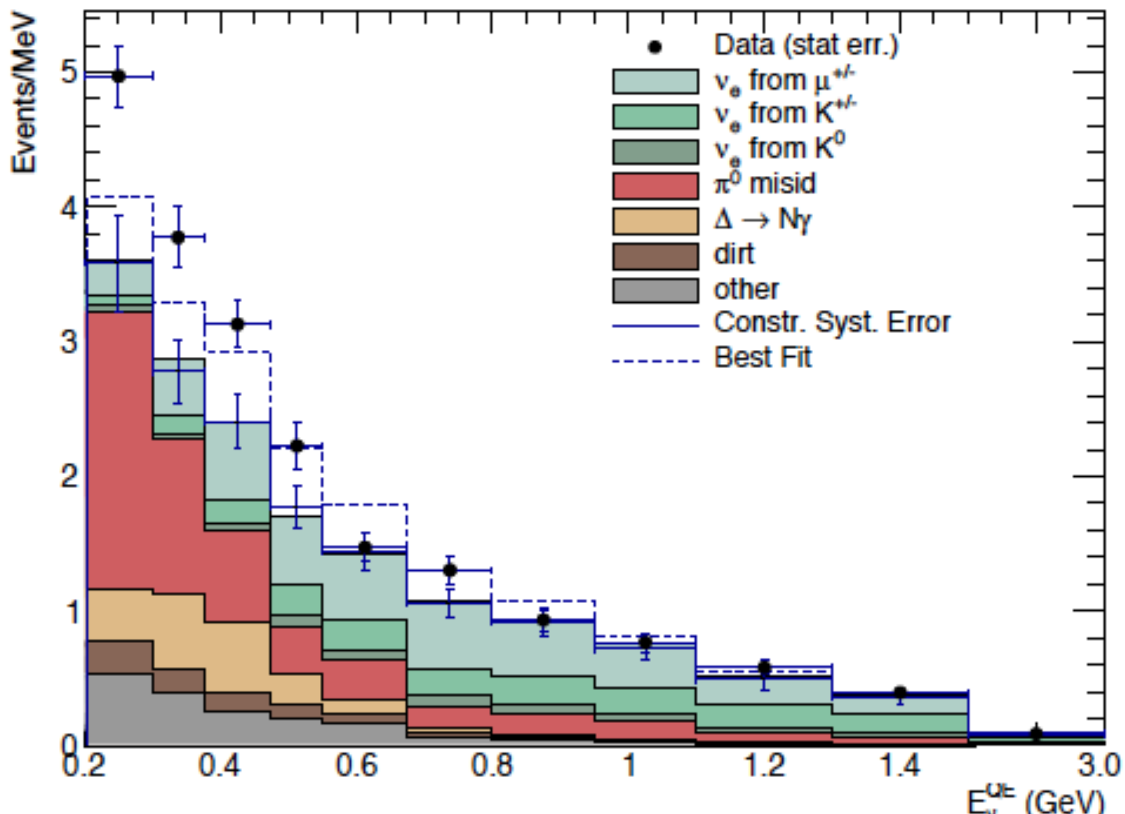


MiniBooNE has;
- higher energy (~500 MeV) than LSND (~30 MeV)
- longer baseline (~500 m) than LSND (~30 m)

1. Oscillation candidate event excess

200 < EνQE < 1250 MeV
- neutrino mode: Data = 1959 events

Bkgd = 1577.8 ± 39.7(stat) ± 75.4(syst) → 381.2 ± 85.2 excess (4.5σ)



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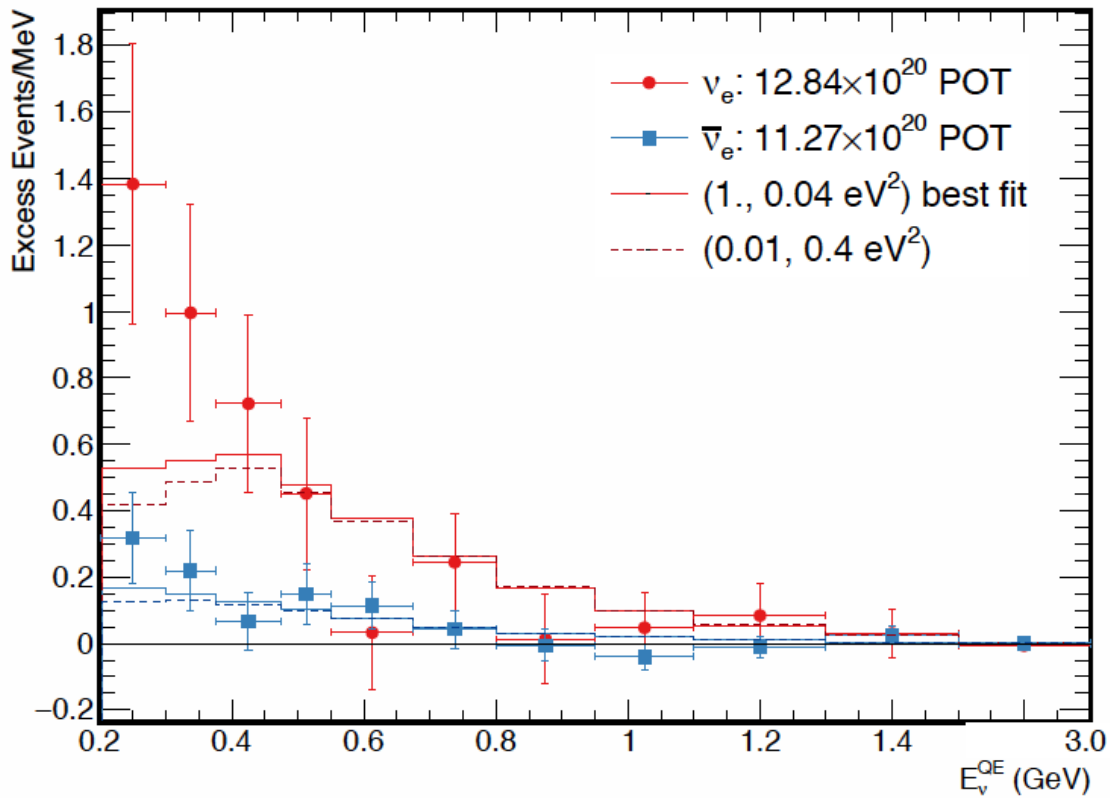
- antineutrino mode: Data = 478 events

Bkgd = 398.7 ± 20.0(stat) ± 20.3(syst) → 79.3 ± 28.6 excess (2.8σ)



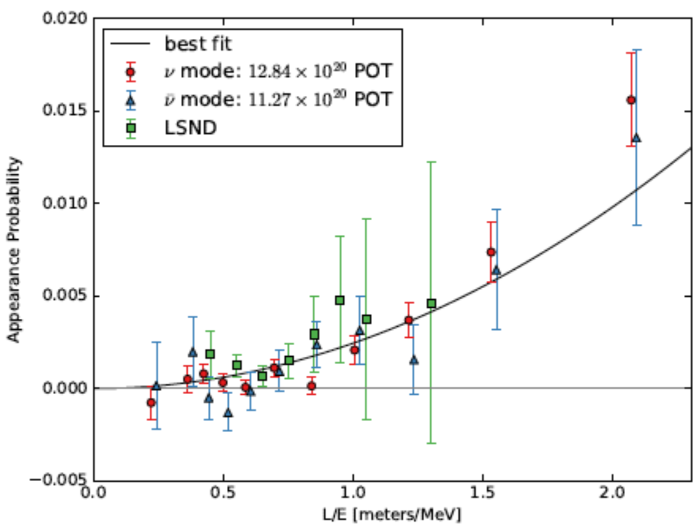
1. 1eV sterile neutrino hypothesis?

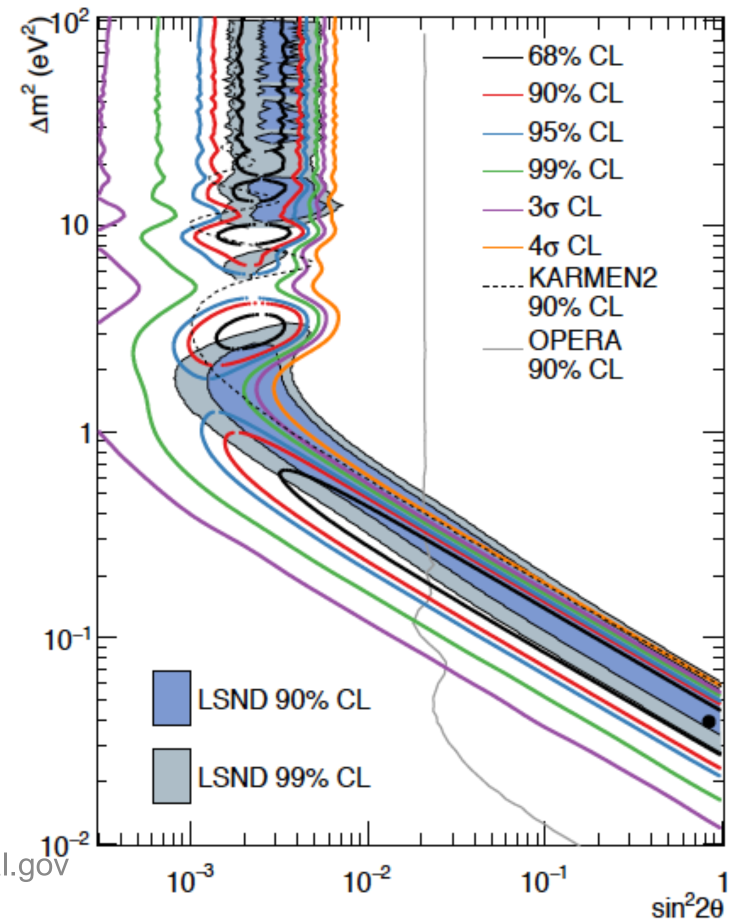
200 < EνQE < 1250 MeV
- neutrino mode: Data = 1959 events

Bkgd = 1577.8 ± 39.7(stat) ± 75.4(syst) → 381.2 ± 85.2 excess (4.5σ)
- antineutrino mode: Data = 478 events

Bkgd = 398.7 ± 20.0(stat) ± 20.3(syst) → 79.3 ± 28.6 excess (2.8σ)

Compatible with LSND excess within 2-neutrino oscillation hypothesis





However, appearance and disappearance data have a strong tension

1. MiniBooNE neutrino experiment

2. Nucleon correlations

3. Pion puzzle

4. NC single photon production

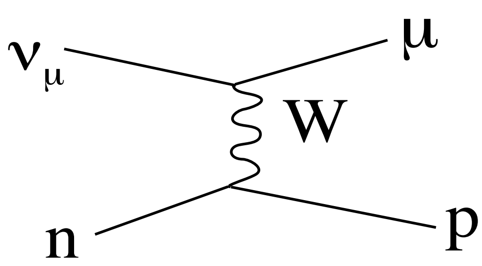
5. Discussions

2. CCQE puzzle

MiniBooNE measured first flux-integrated neutrino-nucleus differential cross section ~1 GeV.

CCQE puzzle

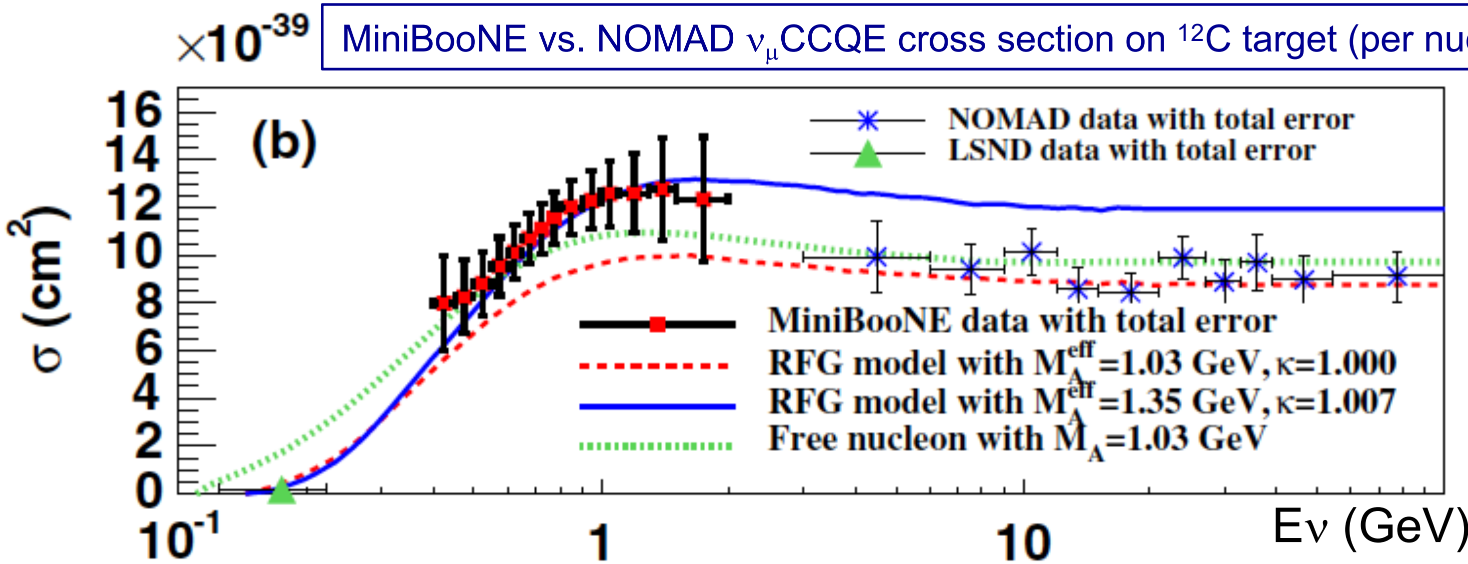
1. low Q2 suppression → Low forward efficiency? (detector?)
2. high Q2 enhancement → Axial mass > 1.0 GeV? (physics?)
3. large normalization → Beam simulation is wrong? (flux?)



CCQE interaction on nuclear targets are precisely measured by electron scattering

- Lepton universality = precise prediction for neutrino CCQE cross-section...?

MiniBooNE vs. NOMAD ν_μCCQE cross section on ^{12}C target (per nucleon)



Martini et al,PRC80(2009)065501;87(2013)065501

2. The solution of CCQE puzzle

Presence of 2-body current in neutrino interactions

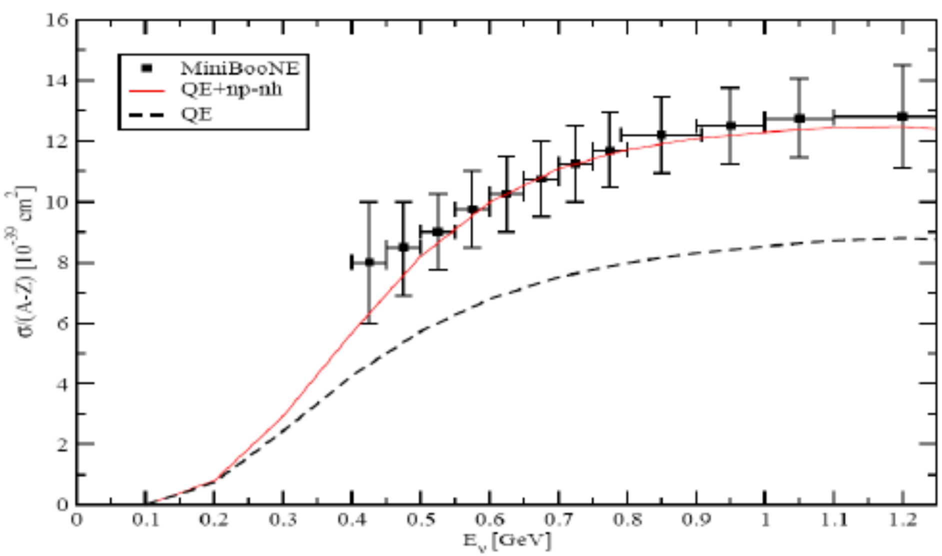
- Martini et al showed 2p-2h effect can add up 10-30% more cross section!

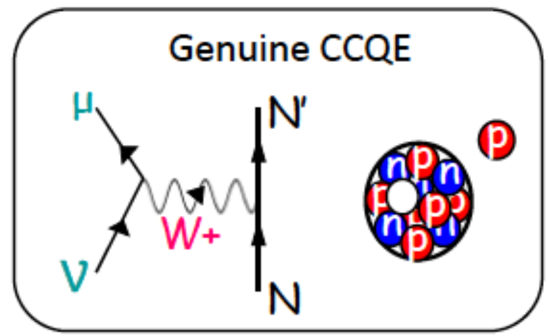
What experimentalists call “CCQE” is not genuine CCQE!

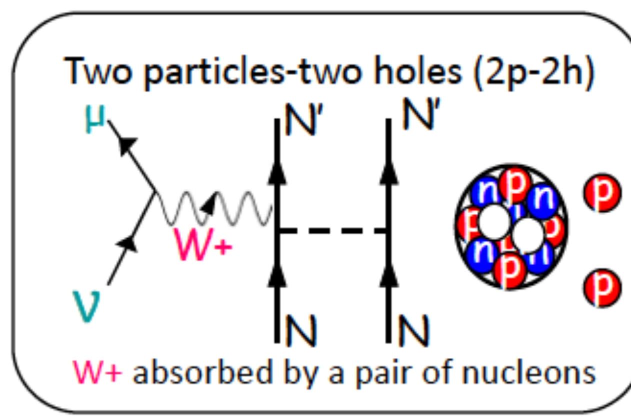
Marco Martini (Saclay)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







Martini et al,PRC80(2009)065501;87(2013)065501
Nieves et al,NPA627(1997)543; PLB707(2012)72;721(2013)90

2. The solution of CCQE puzzle

Presence of 2-body current in neutrino interactions

- Martini et al showed 2p-2h effect can add up 10-30% more cross section!
- consistent result is obtained by Nieves et al

What experimentalists call "CCQE" is not genuine CCQE!

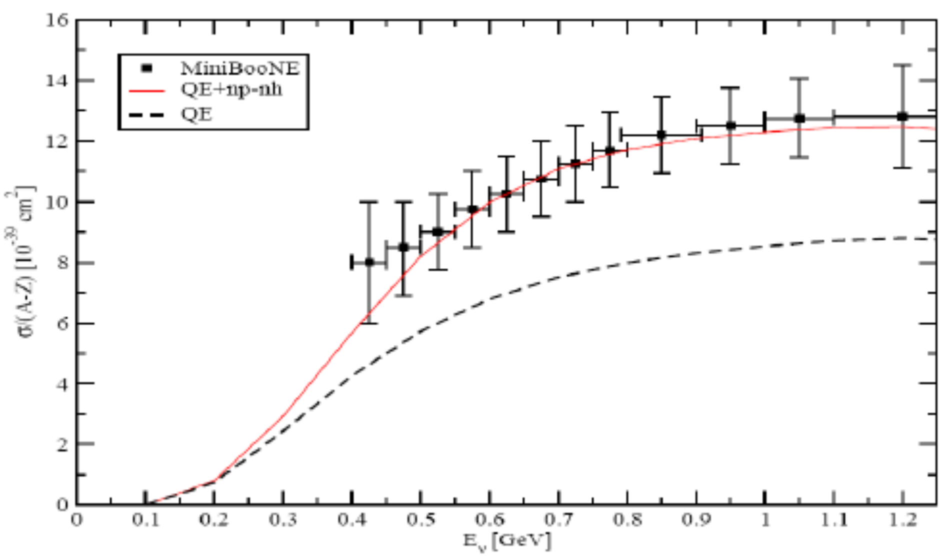
Marco Martini (Saclay)

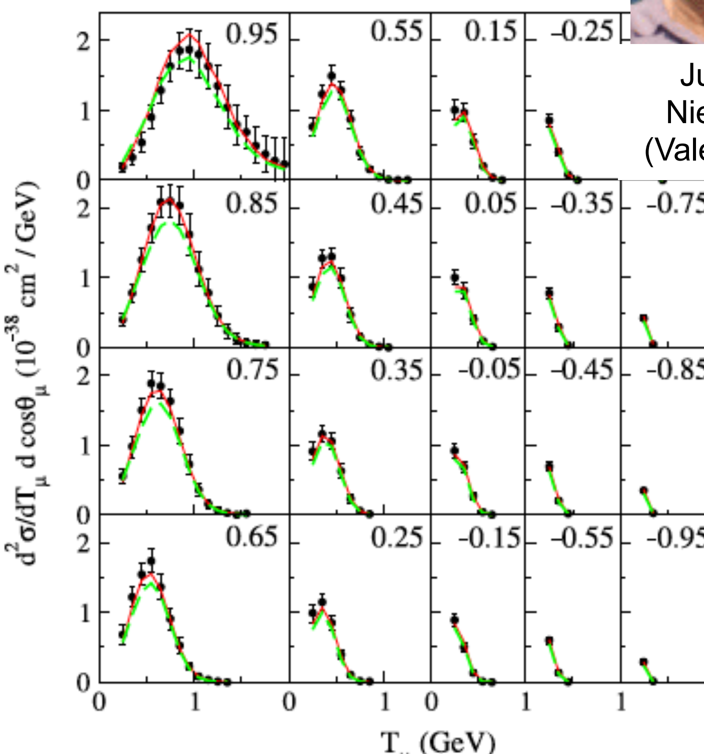
An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)

The model is tuned with electron scattering data (no free parameter)

Juan Nieves (Valencia)





Valencia model vs. MiniBooNE CCQE double differential cross-section data

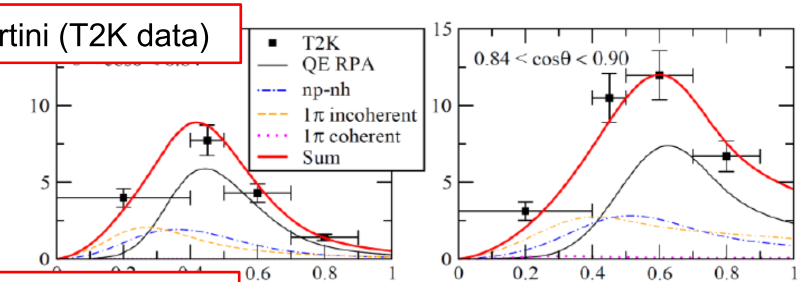
Meucci et al.,PRL107(2011)172501;PRD85(2012)093002;PRD91(2015)093004;Sobczyk,PRC86(2012)015504
Megias et al.,PRD94(2016)093004, Martini and Ericson,PRC90(2014)025501,Gallmeister et al.,PRC94(2016)035502

2. The solution of CCQE puzzle (2016)

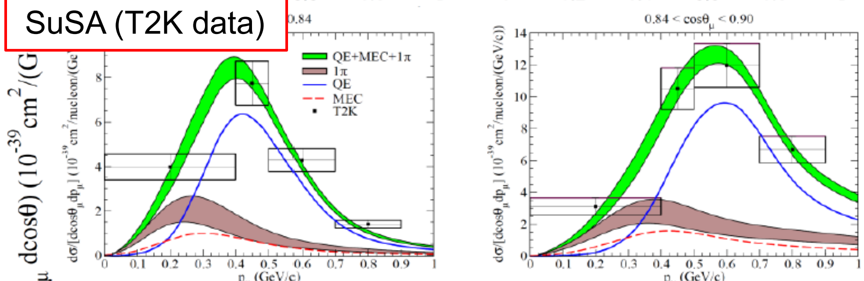
Presence of 2-body current in neutrino interactions

- Martini et al showed 2p-2h effect can add up 10-30% more cross section!
- consistent result is obtained by Nieves et al
- phenomenological models can reproduce MiniBooNE, T2K, MINERvA QE-like ($CC0\pi$) data simultaneously

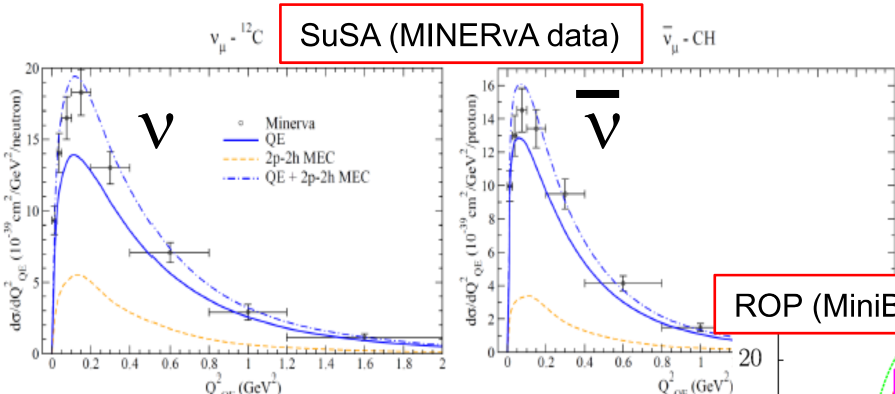
MiniBooNE neutrino beam is not the source of CCQE puzzle
Models reasonably describe lepton kinematics in wide energy region



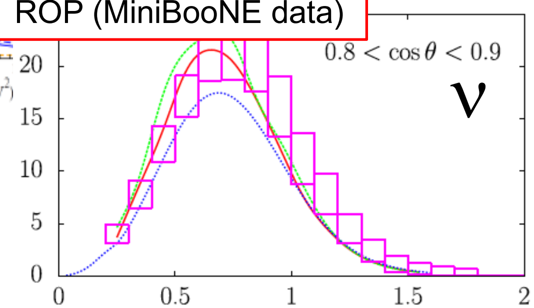
Martini (T2K data)



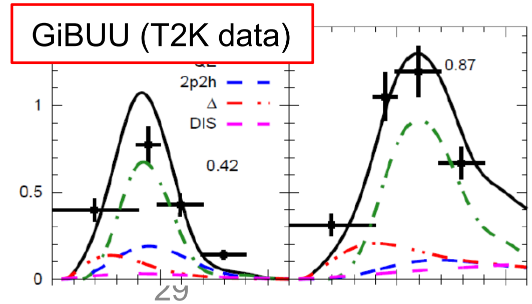
SuSA (T2K data)



SuSA (MINERvA data)



ROP (MiniBooNE data)



GiBUU (T2K data)

Wiringa et al, PRC51(1997)38, Pieper et al, PRC64(2001)014001
Lovato et al,PRL112(2014)182502, PRC91(2015)062501

2. Ab-initio calculation

Ab initio calculation reproduce same feature

Stefano Gandolfi
(Los Alamos)

Quantum Monte Carlo (QMC)

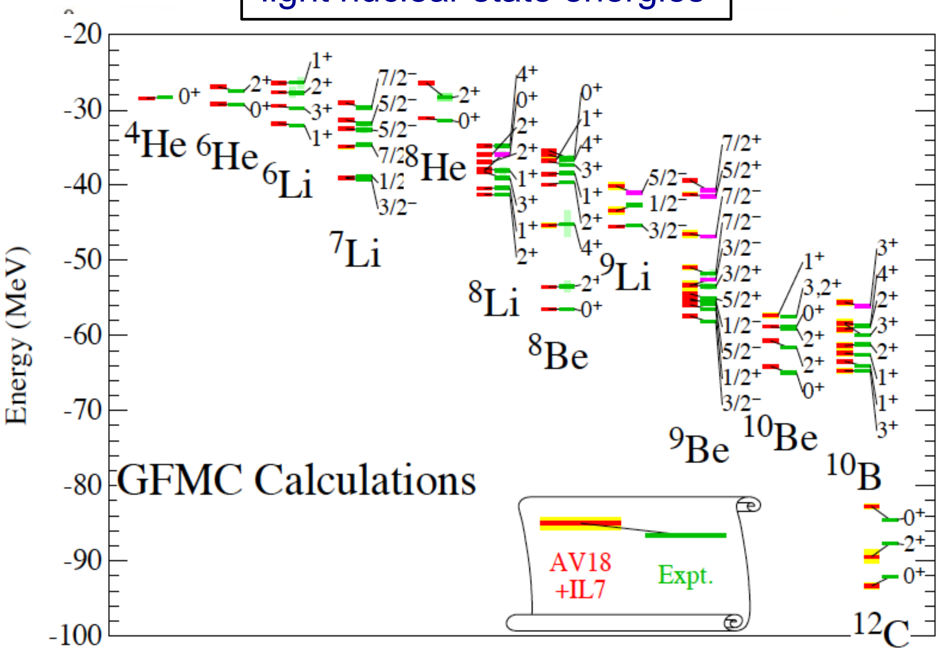
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- neutron-proton short range correlation (SRC)

$$|\Psi_V\rangle = \mathcal{S}\prod_{i<j}^{A}\left[1 + U_{ij} + \sum_{k\neq i,j}^{A} \tilde{U}_{ijk}^{TNI}\right]|\Psi_J\rangle$$

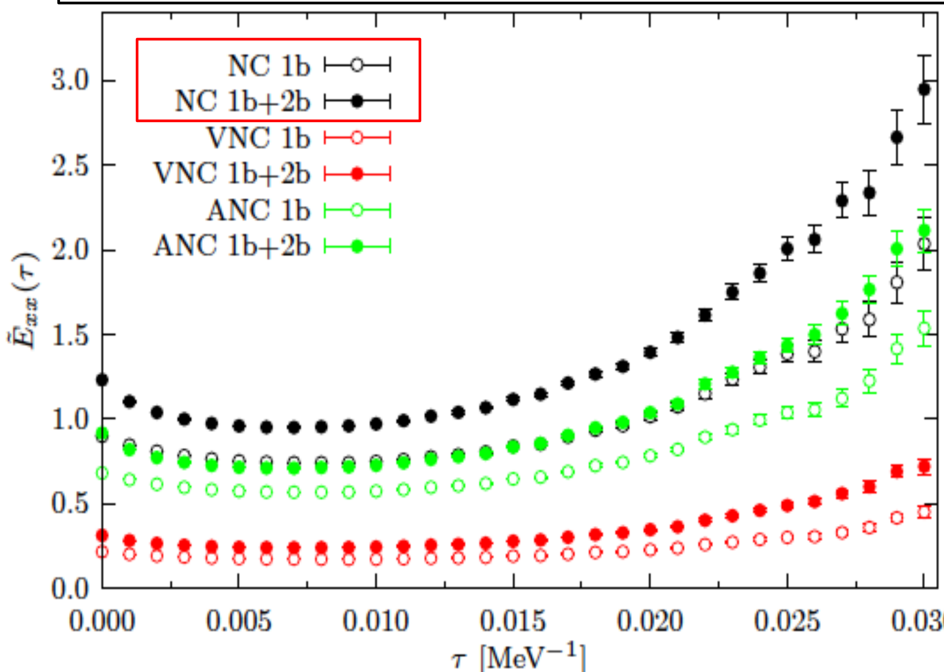
2N potential (Av18)

3N potential (IL7)

light nuclear state energies

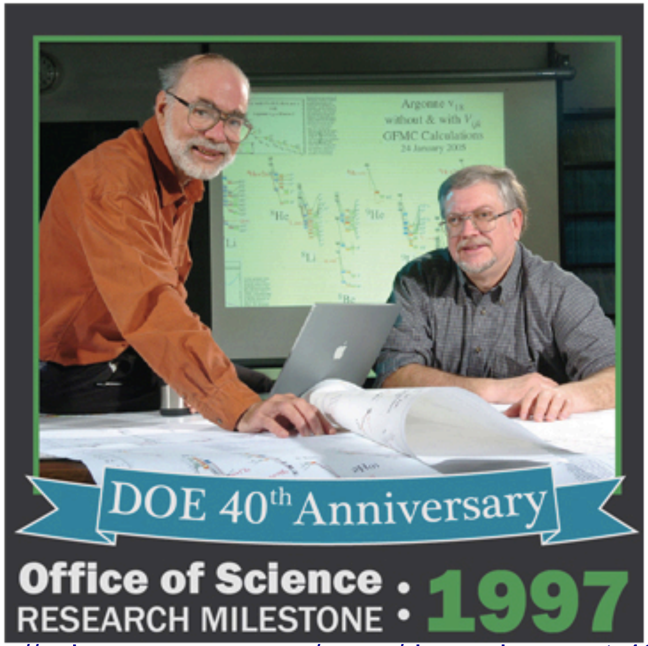


Neutrino NCQE scattering in ^{12}C response function



Pudliner et al., PRC56(1997)1720, Carlson et al, PRC65(2002)024

2. Ab-initio calculation



https://science.energy.gov/news/doe-science-at-40/

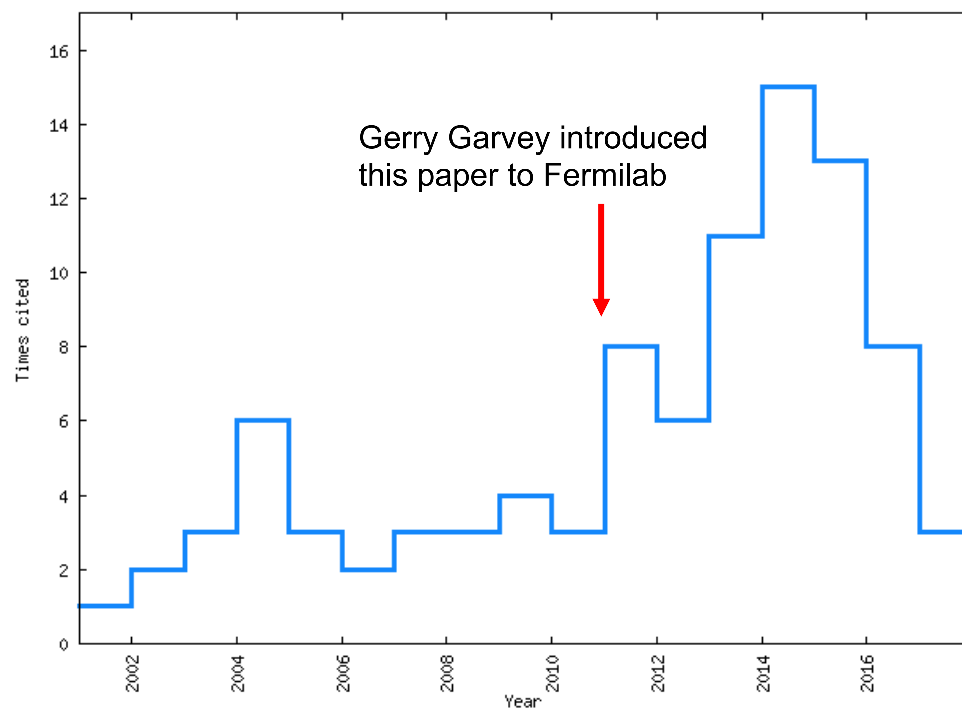
PHYSICAL REVIEW C, VOLUME 65, 024002

Longitudinal and transverse quasielastic response functions of light nuclei

J. Carlson,[1] J. Jourdan,[2] R. Schiavilla,[3,4] and I. Sick[2]
[1]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
[2]*Departement für Physik und Astronomie, Universität Basel, Basel, Switzerland*
[3]*Jefferson Lab, Newport News, Virginia 23606*
[4]*Physics Department, Old Dominion University, Norfolk, Virginia 23529*
(Received 21 June 2001; published 25 January 2002)

The ^{3}He and ^{4}He longitudinal and transverse response functions are determined from an analysis of the world data on quasielastic inclusive electron scattering. The corresponding Euclidean response functions are derived and compared to those calculated with Green's function Monte Carlo methods, using realistic interactions and currents. Large contributions associated with two-body currents are found, particularly in the ^{4}He transverse response, in agreement with data. The contributions of the two-body charge and current operators in the ^{3}He, ^{4}He, and ^{6}Li response functions are also studied via sum-rule techniques. A semiquantitative explanation for the observed systematics in the excess of transverse quasielastic strength, as function of mass number and momentum transfer, is provided. Finally, a number of model studies with simplified interactions, currents, and wave functions are carried out to elucidate the role played, in the full calculation, by tensor interactions and correlations.

DOI: 10.1103/PhysRevC.65.024002 PACS number(s): 25.30.Fj, 25.10.+s, 21.45.+v



Physics of nucleon correlations

- response functions (neutrino interaction)
- form factors (dark matter interaction)
- EMC effect (particle physics)
- matrix element ($0\nu\beta\beta$)
- etc

Gerry Garvey beats me by arm-wrestling (2016)

Queen Mary University of London

2. Nucleon correlation models in neutrino physics

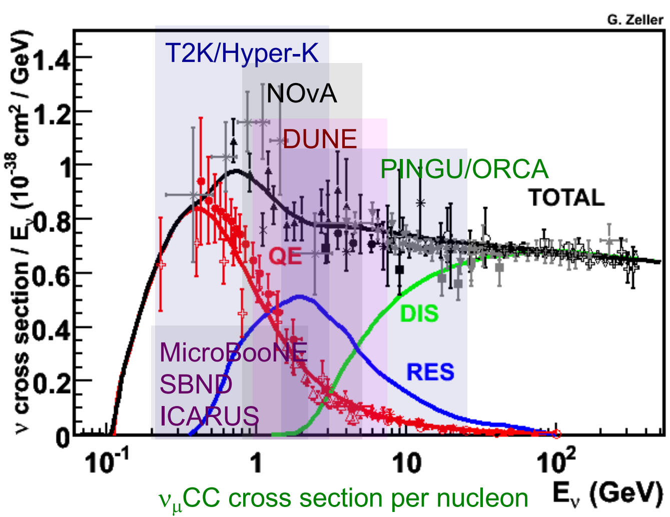
The community agrees nucleon correlations are important for neutrino oscillation physics
- Significant enhancement of cross section (10-30%)
- modify lepton kinematics and final state hadrons
- the hottest topic for T2K, MINERvA, MicroBooNE, etc

Particle Data Group
- Section 42, “Monte Carlo Neutrino Generators” (Hugh Gallagher, Yoshinari Hayato)
- Section 50, “Neutrino Cross-Section Measurements” (Sam Zeller)

Status

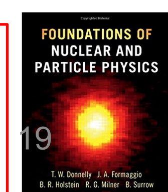
Currently, Valencia 2p-2h+RPA model is used by neutrino interaction generator to simulate QE region interaction (T2K, NOvA, MicroBooNE, etc).

What about nucleon correlations for pion productions and higher energy processes?



Nucleon correlations for QE-region is important for T2K, HyperK, MicroBooNE/SBND/ICARUS, but other experiments need to worry nucleon correlation physics for higher energy processes

The first textbook of neutrino interaction physics!
“Foundation of Nuclear and Particle Physics”
- Cambridge University Press (2017), ISBN:0521765110
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow



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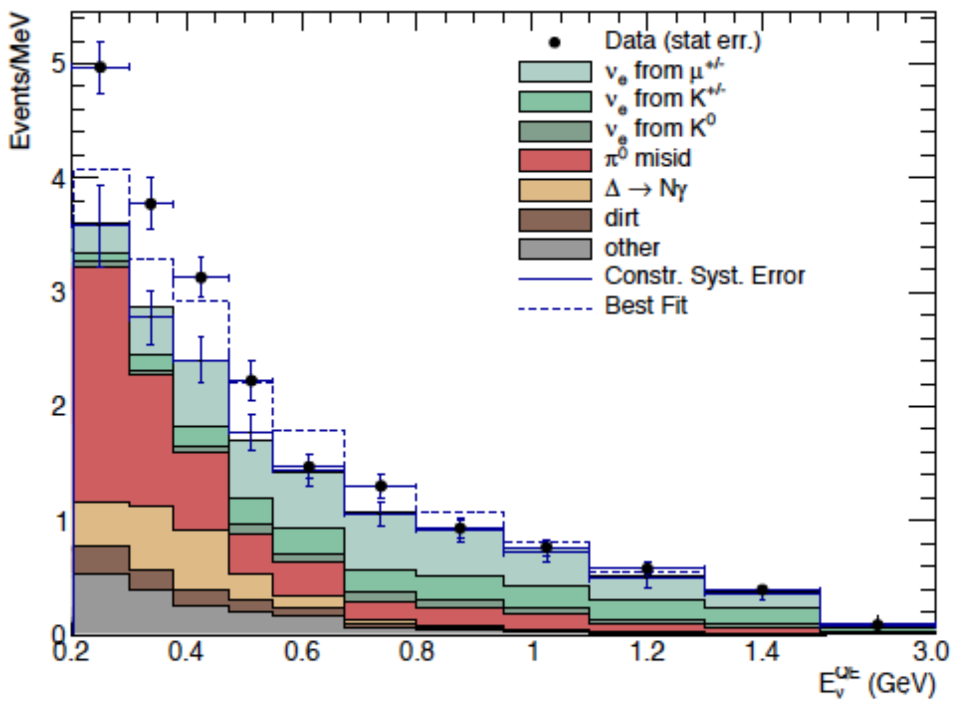
5. Discussions

3. MiniBooNE excess data

All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E

	Process	Neutrino Mode	Antineutrino Mode
misID	ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
	NC π^0	501.5 ± 65.4	112.3 ± 11.5
	NC $\Delta \to N\gamma$	172.5 ± 24.1	34.7 ± 5.4
	External Events	75.2 ± 10.9	15.3 ± 2.8
	Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
intrinsic	ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
	ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
	ν_e & $\bar{\nu}_e$ from K^0_L Decay	54.5 ± 20.5	51.4 ± 18.0
	Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0
	Unconstrained Bkgd.	1590.5	398.2
	Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
	Total Data	1959	478
	Excess	381.2 ± 85.2	79.3 ± 28.6



3. Intrinsic beam ν_e background

All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
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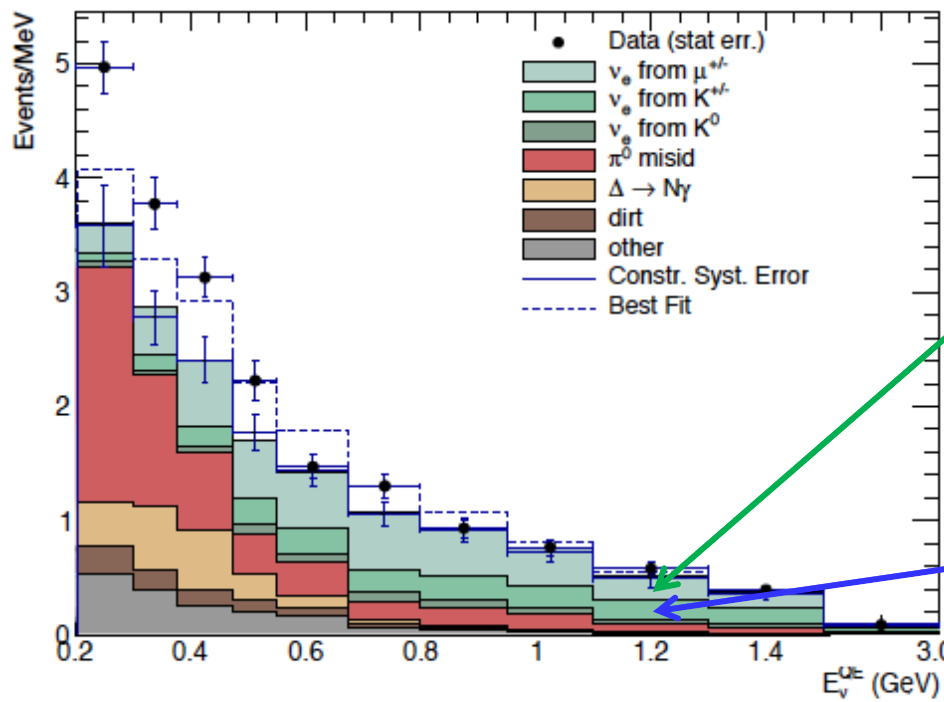
Intrinsic beam ν_e backgrounds are less likely to be the cause of excess



ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

3. π^o background

All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
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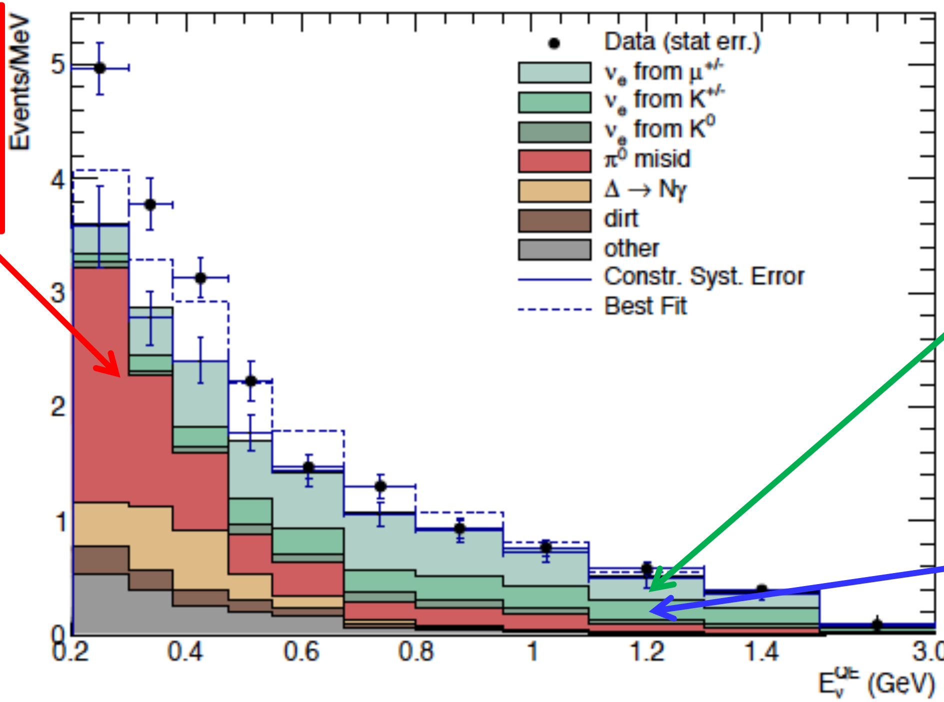
Asymmetric π^o decay is constrained from measured $CC\pi^o$ rate ($\pi^o \to \gamma$)



ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

3. γ from π^o constraint

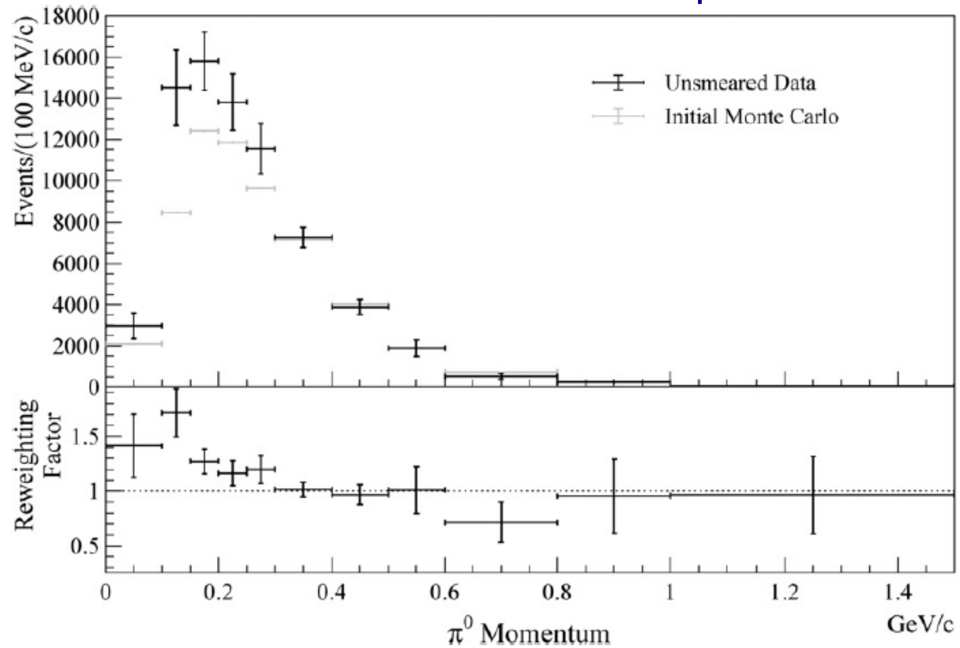
$\pi^o \rightarrow \gamma\gamma$
- not background, we can measure

$\pi^o \rightarrow \gamma$
- misID background, we cannot measure

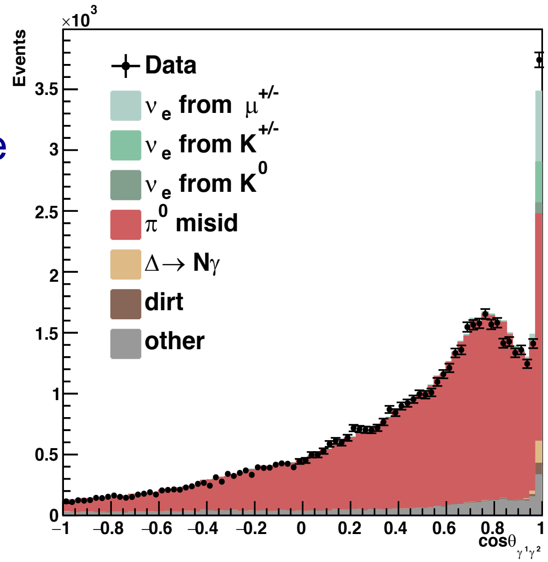
The biggest systematics is production rate of π^o, because once you find that, the chance to make a single gamma ray is predictable.

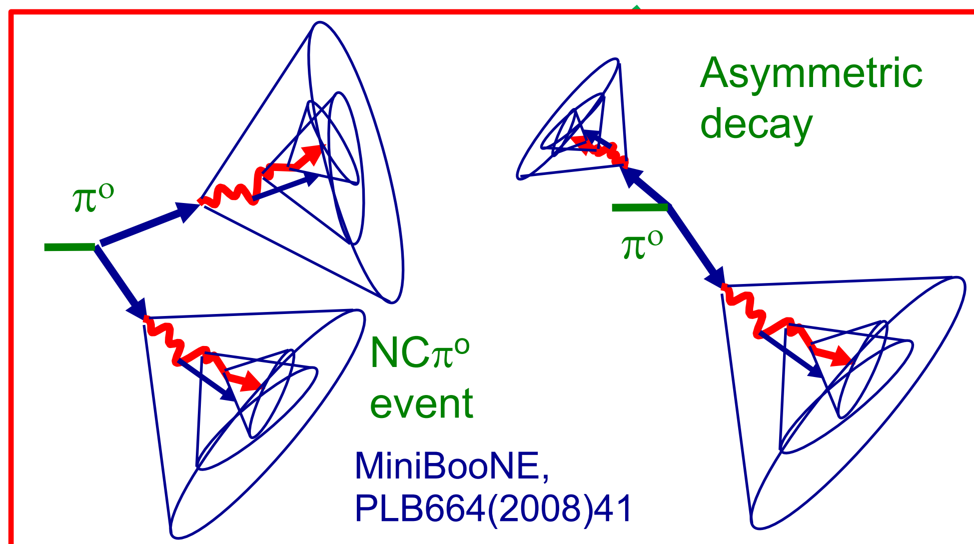
We measure π^o production rate, and correct simulation with function of π^o momentum

π^o momentum data-MC comparison



2-gamma-ray opening angle





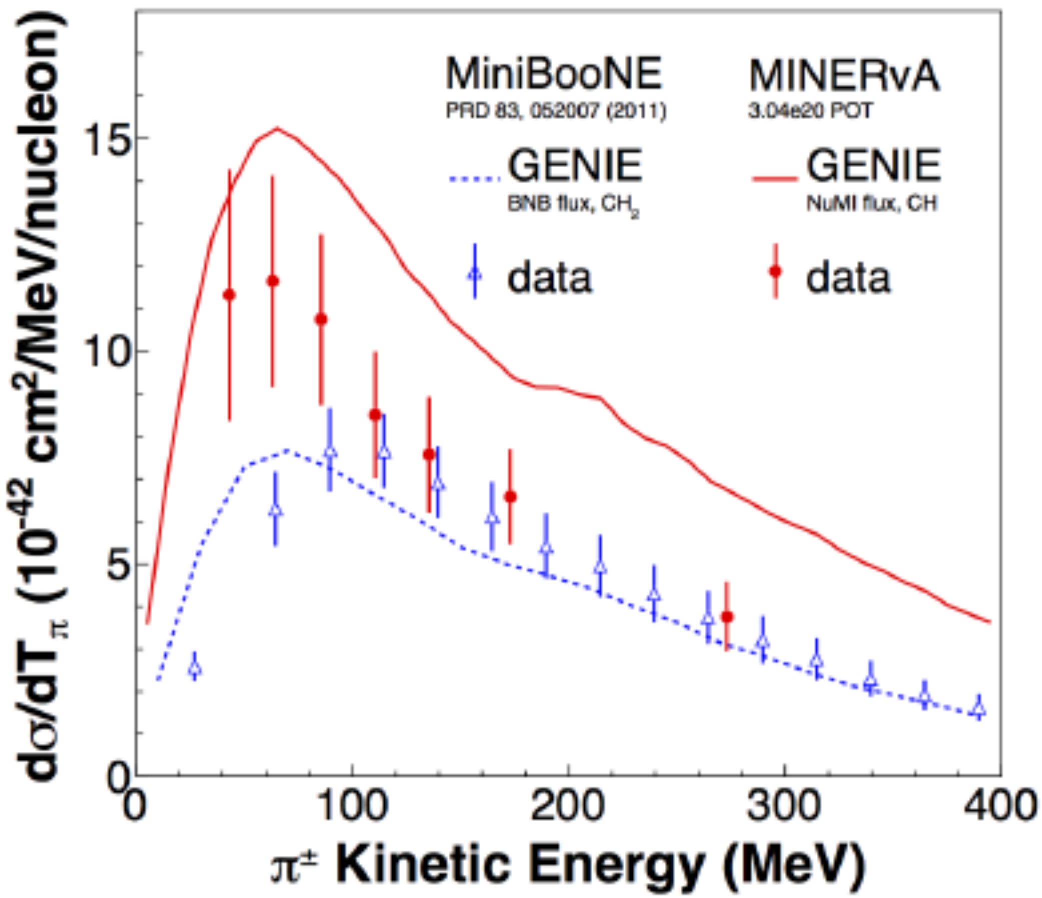
3. Pion puzzle (2015)

Data from MiniBooNE and MINERvA and simulation are all incompatible

Flux-integrated differential cross-section are not comparable (unless 2 experiments use same neutrino beam)

Two data set are related by a model (=GENIE neutrino interaction generator).

MINERvA data describe the shape well, but MiniBooNE data have better normalization agreement…



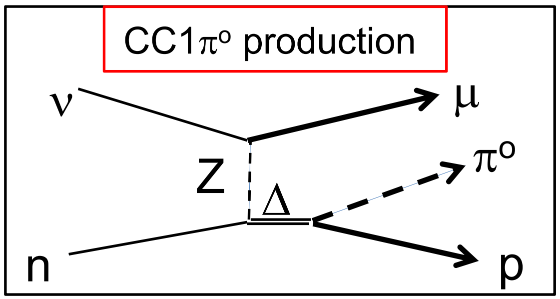
3. Pion puzzle (2015)

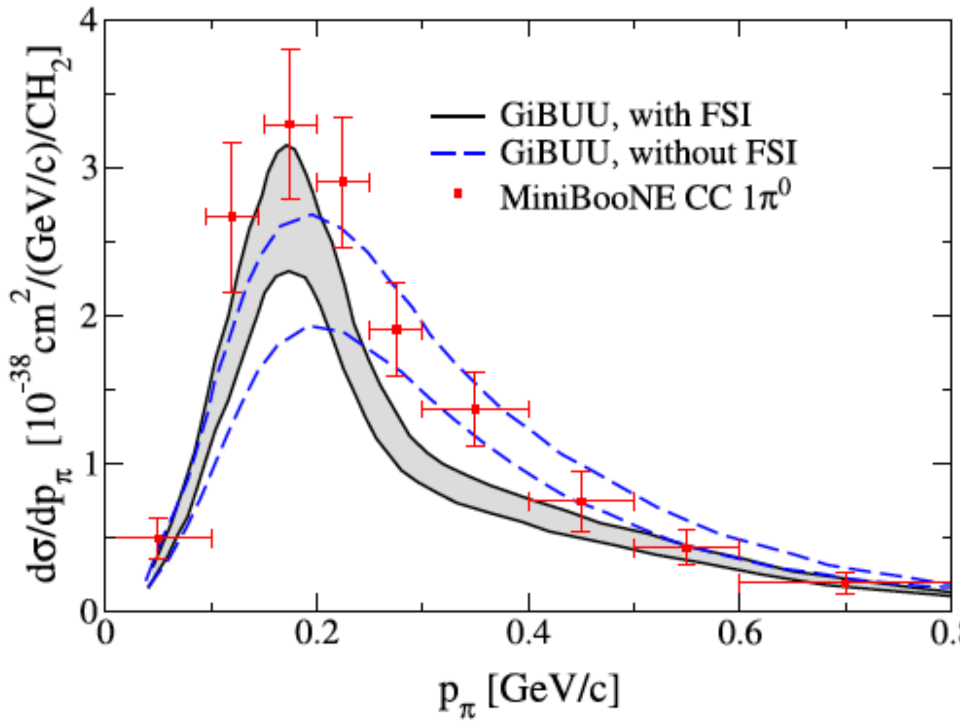
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

Ulrich Mosel (Giessen)

Final state interaction

- Cascade model as a standard of the community
- Advanced models are not available for event-by-event simulation





ex) Giessen BUU transport model

- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

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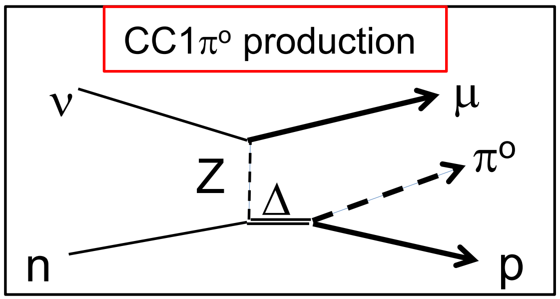

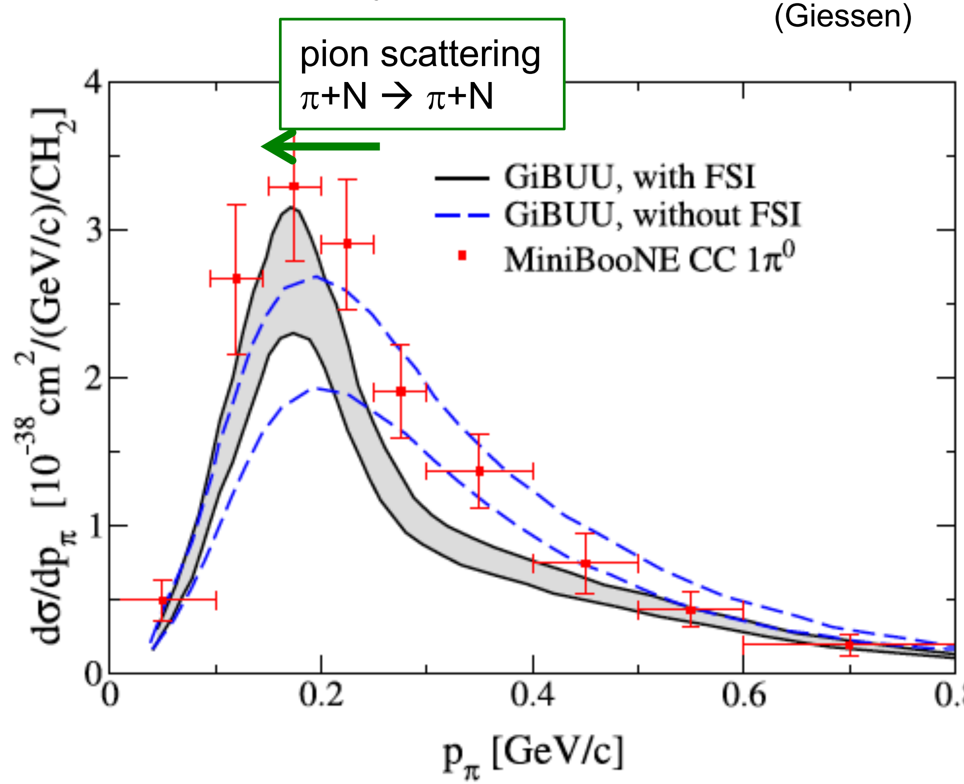

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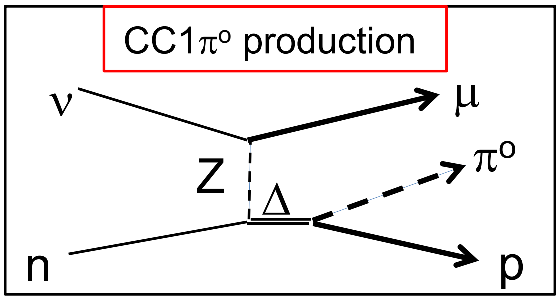

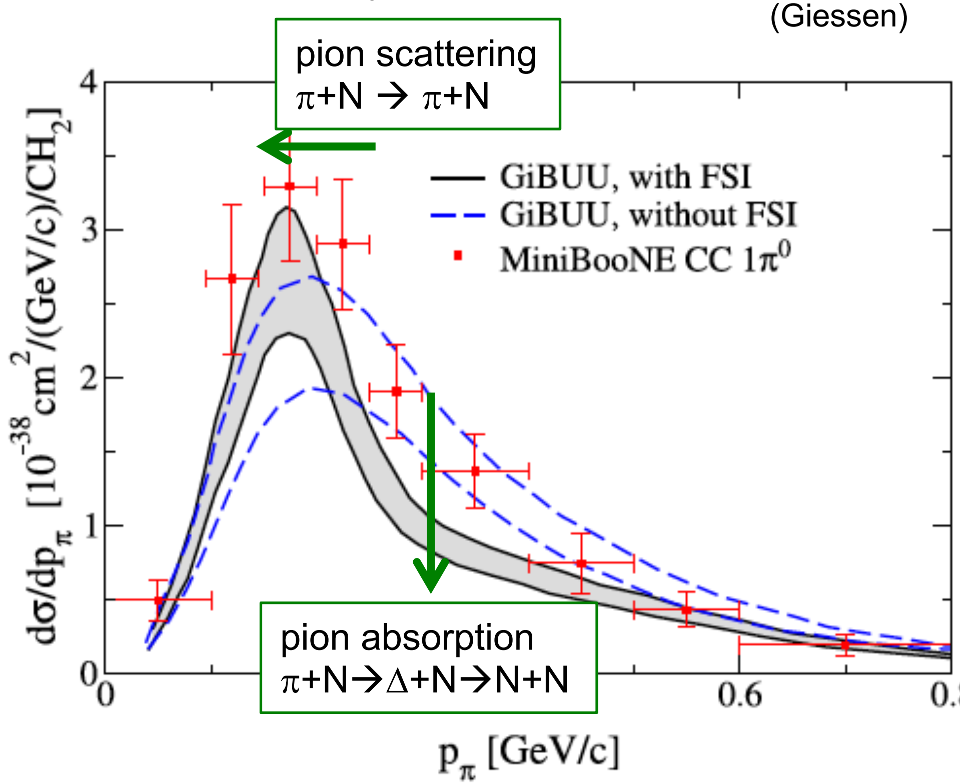

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Queen Mary University of London

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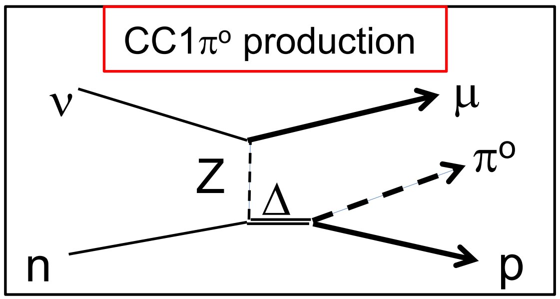
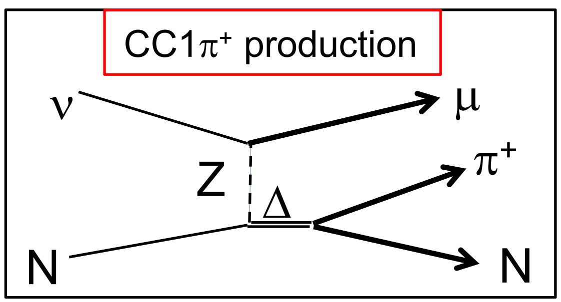
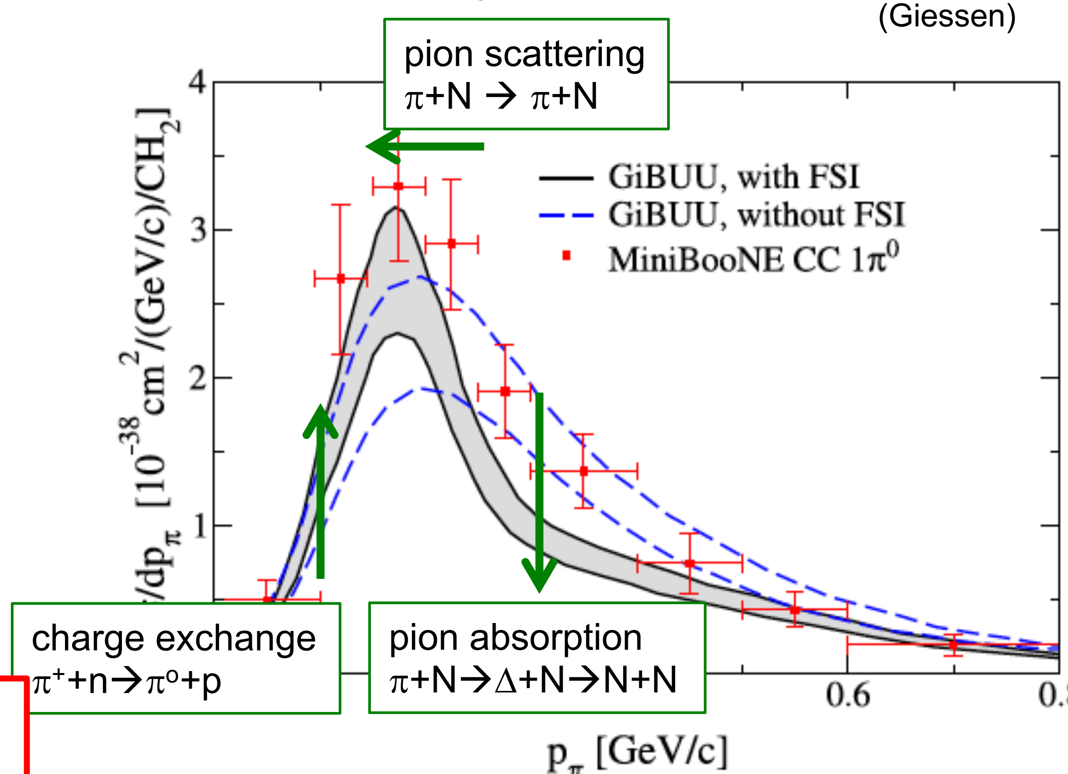






You need to predict both
1. pion production model
2. final state interaction

ex) Giessen BUU transport model
- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

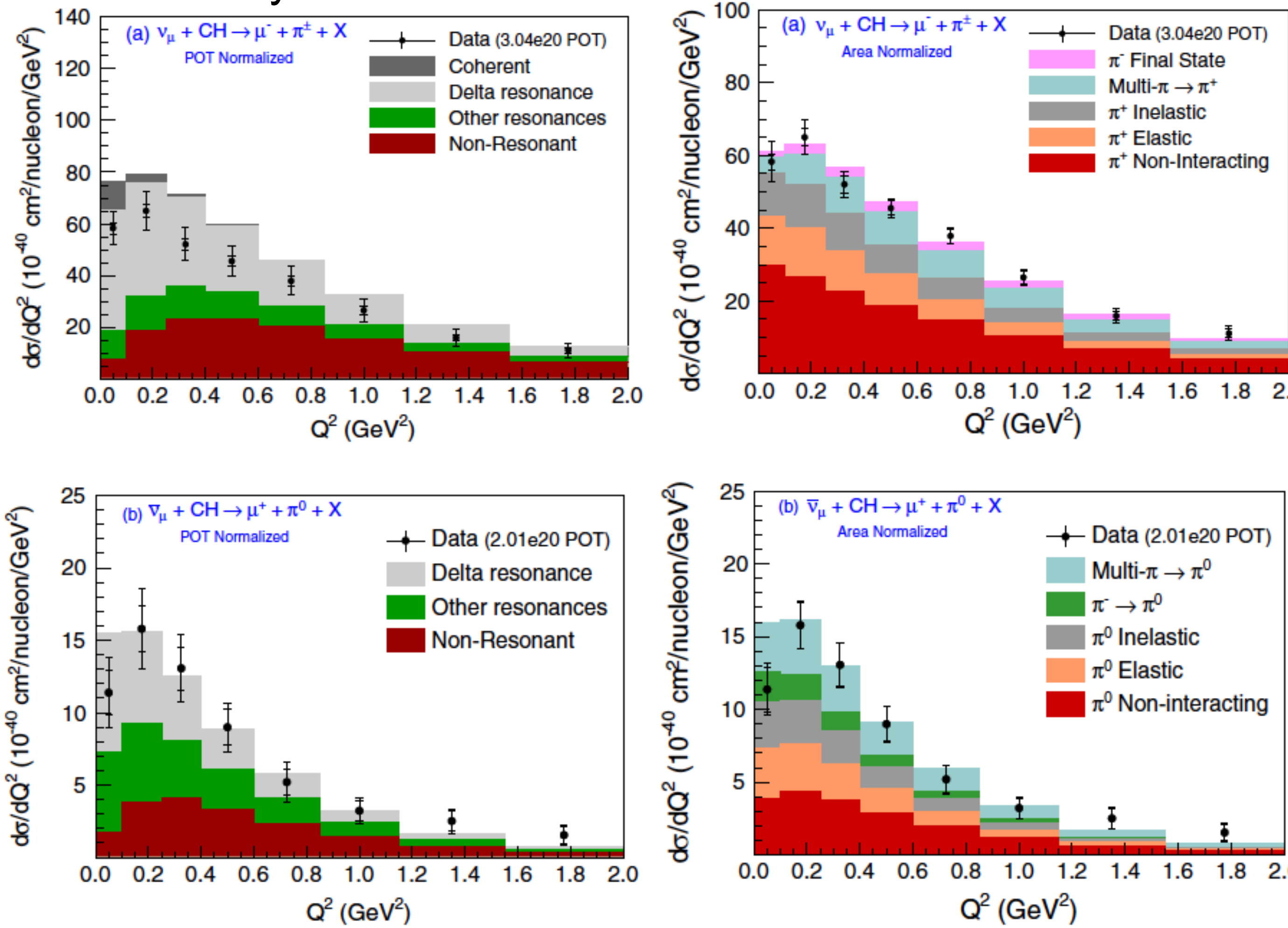
3. Pion puzzle (2016)

MINERvA CC1π^+, $\bar{\nu}$CC1π^o data for FSI + cross section models tuning

- this moment, there is no clear way to tune MC from data…

ν_μCC1π^+ data have better shape agreement with GENIE

$\bar{\nu}$CC1π^o data have better normalization agreement with GENIE



3. Pion puzzle (2019)

MINERvA CC1π^+, CCNπ^+, $\bar{\nu}$CC1π^o, νCC1π^o data for FSI + cross section models tuning

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CC1π^+ and CCNπ^+ data have better shape agreement with GENIE

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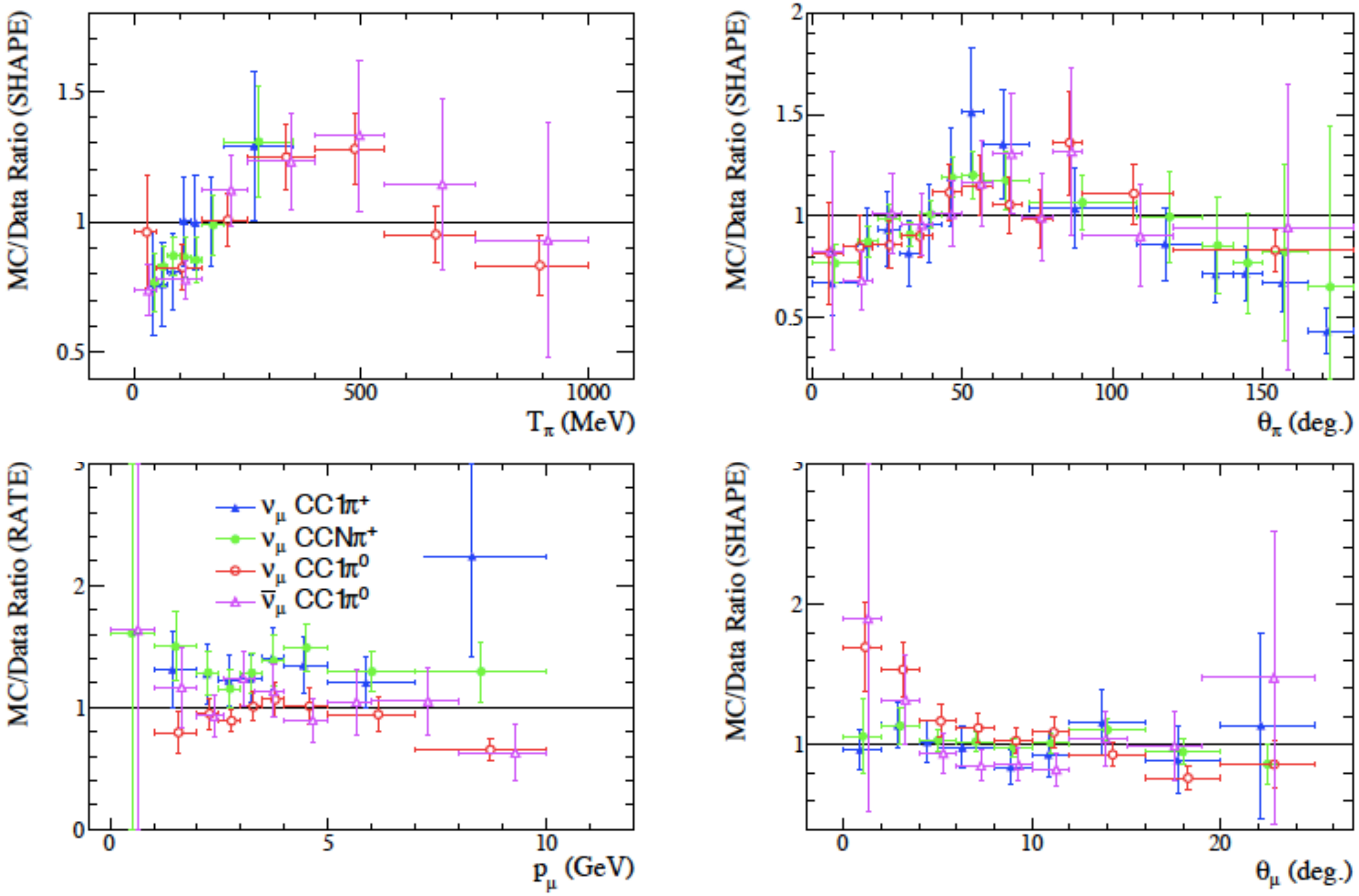

3. Pion puzzle (2019)

MINERvA CC1π^+, CCNπ^+, $\bar{\nu}$CC1π^o, νCC1π^o data for FSI + cross section models tuning
- this moment, there is no clear way to tune MC from data…

GiBUU shows good agreement with all MINERvA (carbon) and T2K (carbon and water) pion data, but not MiniBooNE data.

Solving pion puzzle is extremly important for future, especially for DUNE;
- heavy target (argon)
- pion production channels are signal (not background, unlike T2K and MiniBooNE)

Do nucleon correlations play important role for neutirno pion production models?

1. MiniBooNE neutrino experiment

2. Nucleon correlations

3. Pion puzzle

4. NC single photon production

5. Discussions

4. NCγ constraint

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
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Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6

All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
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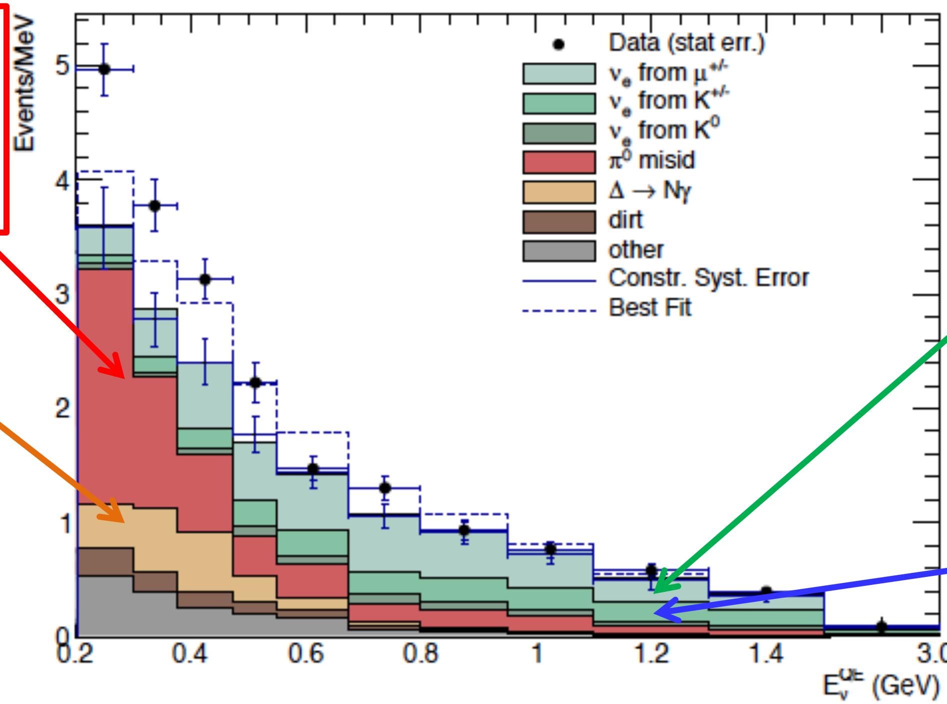
Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \to \gamma$)

Δ resonance rate is constrained from measured NCπ^o rate



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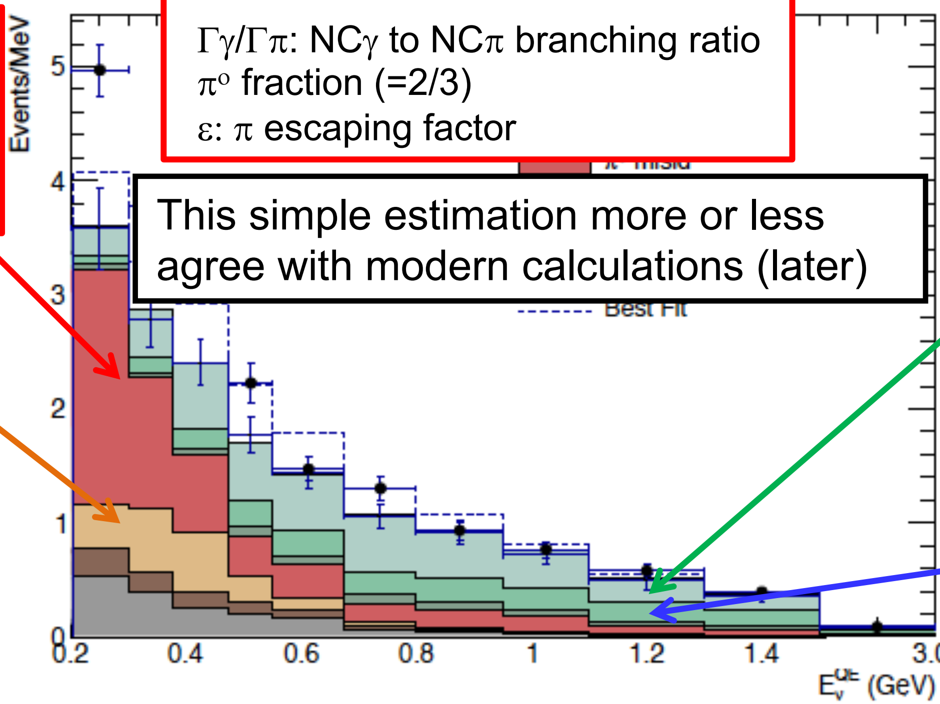
$$\frac{N(\Delta \to N\gamma)}{N(\Delta \to N\pi^o)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^o}\varepsilon}$$

Γγ/Γπ: NCγ to NCπ branching ratio
π° fraction (=2/3)
ε: π escaping factor



This simple estimation more or less agree with modern calculations (later)

Asymmetric π° decay is constrained from measured CCπ° rate (π°→γ)

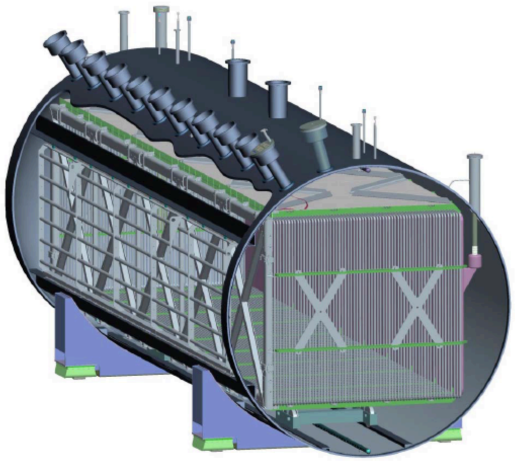
Δ resonance rate is constrained from measured NCπ° rate

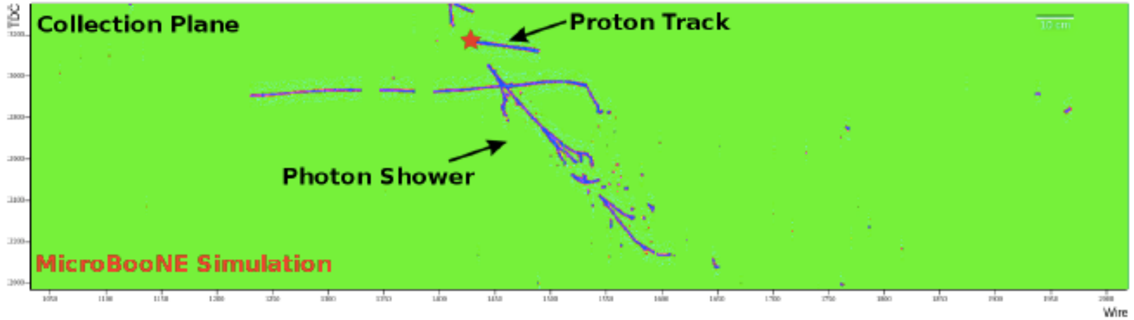
ν_e from μ decay is constrained from ν_μCCQE measurement

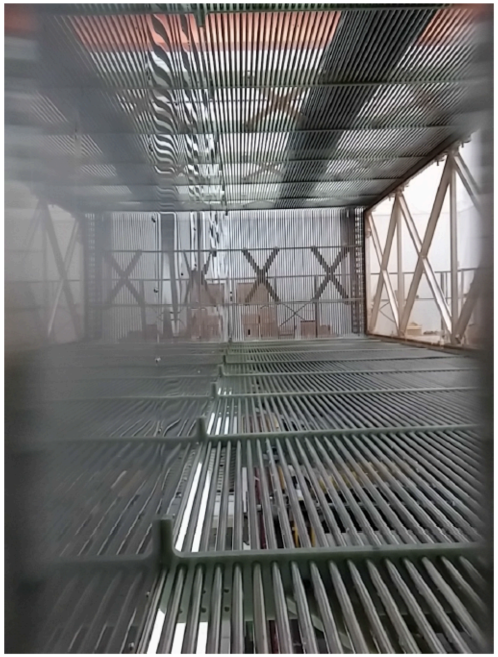
ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

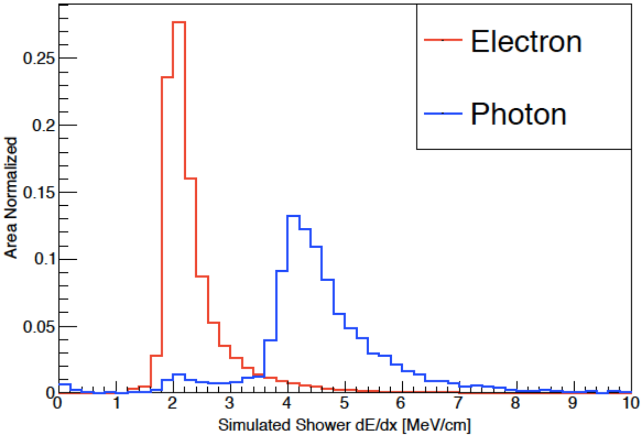
4. Liquid argon time projection chamber

High resolution detector with e/γ separation
- Original motivation of US LArTPC program







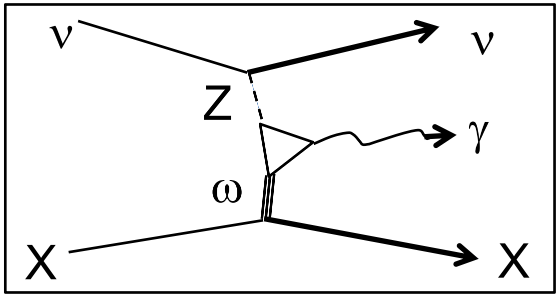


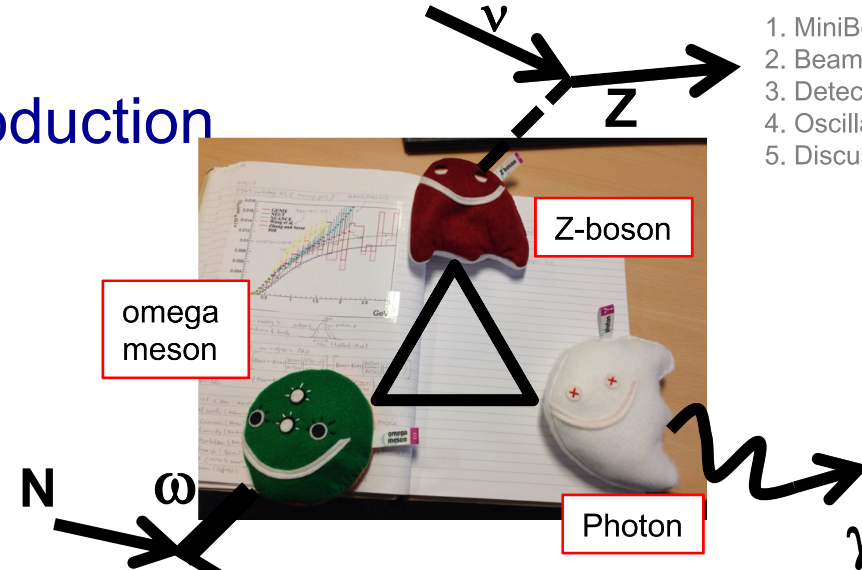
dE/dx of first 4cm track (simulation)

4. Neutrino NC single photon production

Anomaly mediated γ production

- process within SM, but not considered.

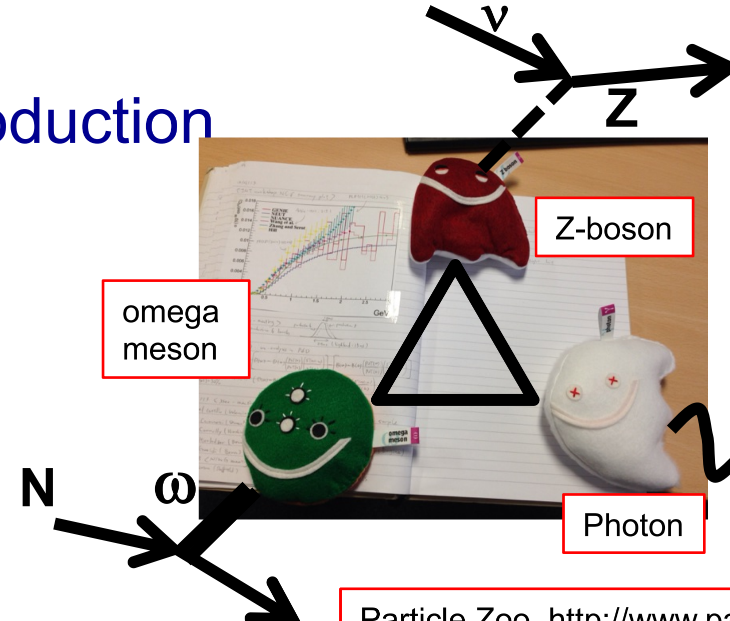




Particle Zoo, http://www.particlezoo.net/

Harvey,Hill,Hill, PRL99(2007)261601
Lasorak, PhD thesis (Queen Mary, 2018)

4. Neutrino NC single photon production



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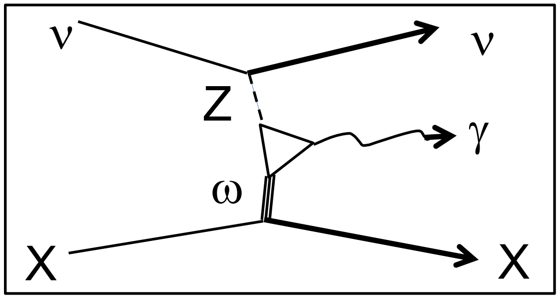
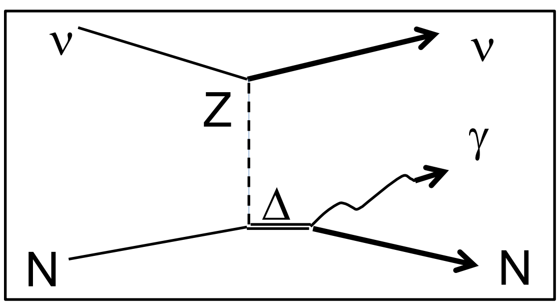
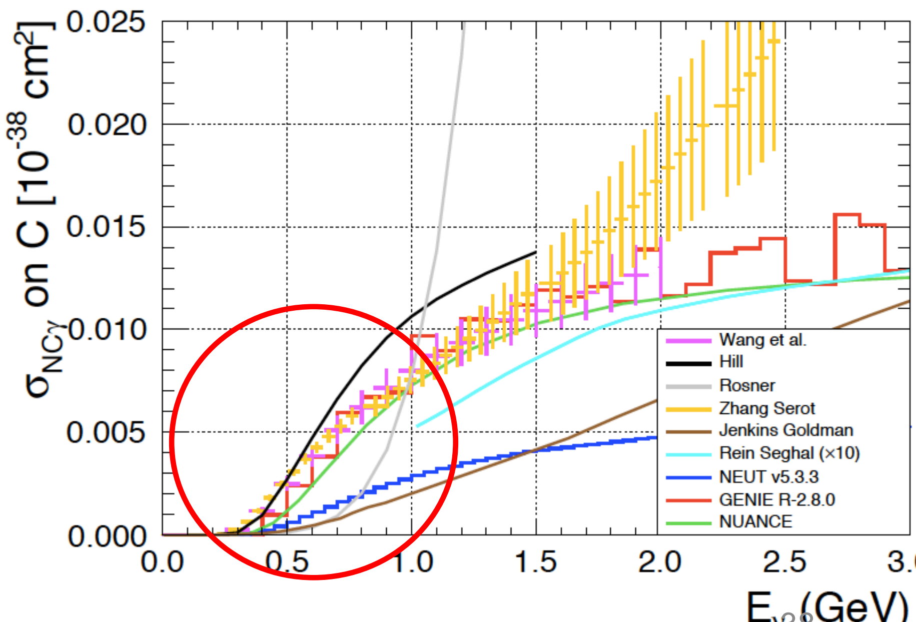


A lot of new calculations

- Δ-radiative decay with nuclear corrections.
- all theoretical models and generators more or less agree in MiniBooNE energy region.

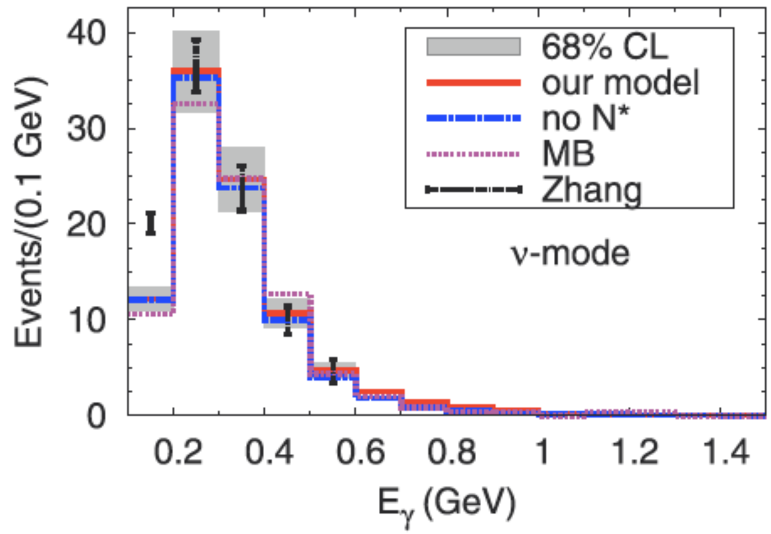




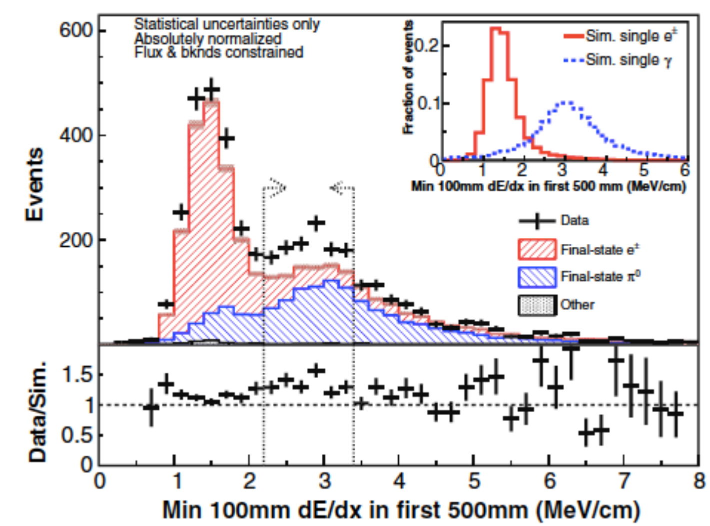
Hill, PRD84(2011)017501, Zhang and Serot, PLB719(2013)409, Wang et al, PLB740(2015)16
MINERvA, PRL117(2016)111801

4. Neutrino NC single photon production

NC γ production prediction for MiniBooNE
- MiniBooNE provides efficiency tables to convert theory → experimental distribution
- New models are more or less consistent with MiniBooNE NCγ model



Are we missing any other background processes?
- It's easy to forget processes with $\sigma \sim 10^{-41}$ cm^2 (e.g., diffractive π^o production σ(1GeV) ~ 10^{-41} cm^2 was identified very recently by MINERvA, also neglected by all simulations)

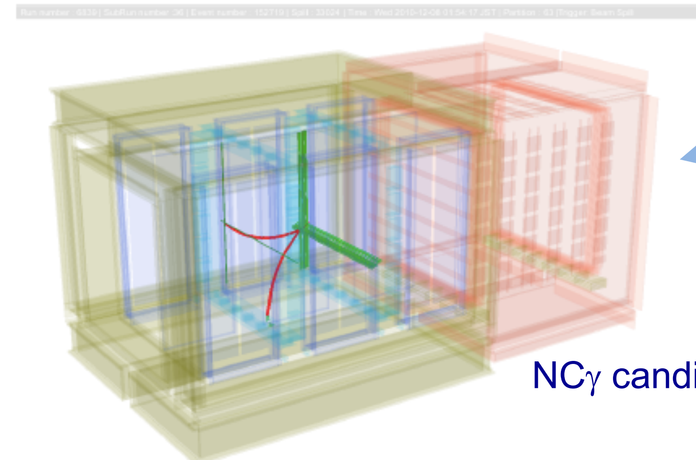


T2K, ArXiv:1902.03848
MicroBooNE, public note 1041 (2018)

4. Neutrino NC single photon production

T2K near detector

- 95% pure photon sample (M_{inv}<50 MeV)
- Large external photon background and internal π^o production background. T2K can only set a limit.

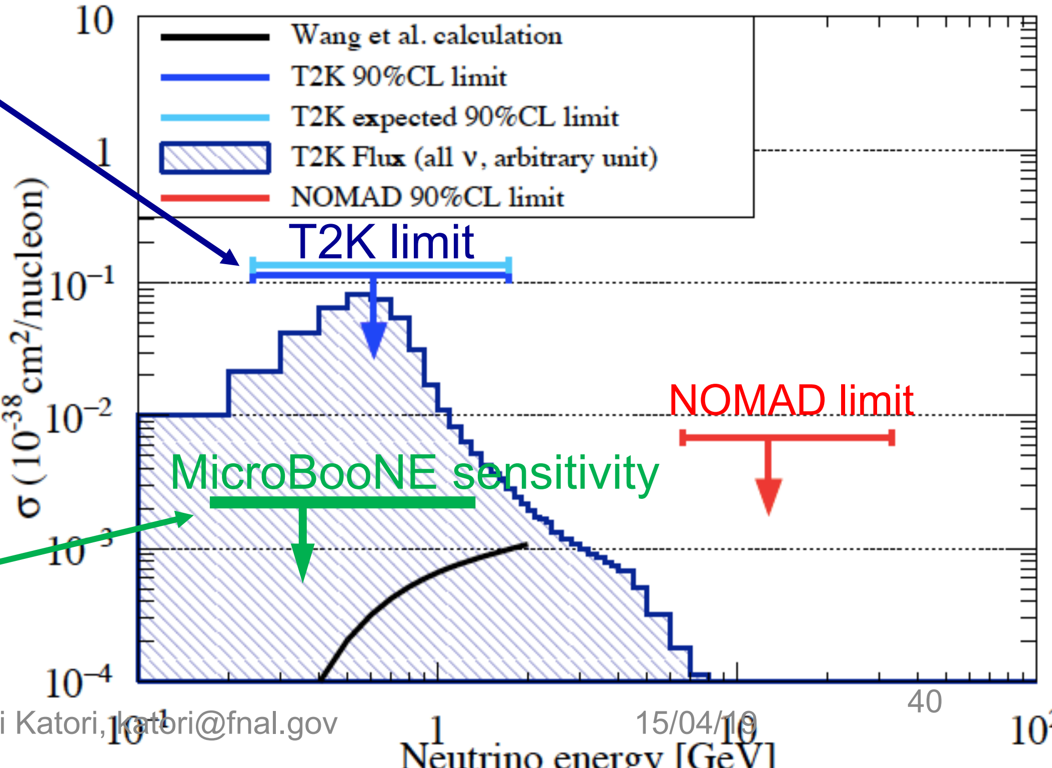


Pierre Lasorak
Queen Mary (T2K)
→ Sussex (DUNE)

MicroBooNE

- First large ν-LArTPC in USA
- Good e/γ PID
- Large active veto region
- Good internal π^o measurement

→ Good chance to measure the first positive signal of this channel.



Bobby Murrell
Manchester
(MicroBooNE)

Queen Mary
University of London

4. Neutrino NC single photon production

NCγ is unlike source of the MiniBooNE excess

So far no experiment can identify NCγ process

However, NCg is one of the major backgrounds for future high statistics ν_e appearance experiments (HyperK, possibly DUNE). Currently we assign 100% systematic error so any new measurements would improve the situation.

Can ab initio calculation predict NCγ cross section precisely?

1. MiniBooNE neutrino experiment

2. Nucleon correlations

3. Pion puzzle

4. NC single photon production

5. Discussions

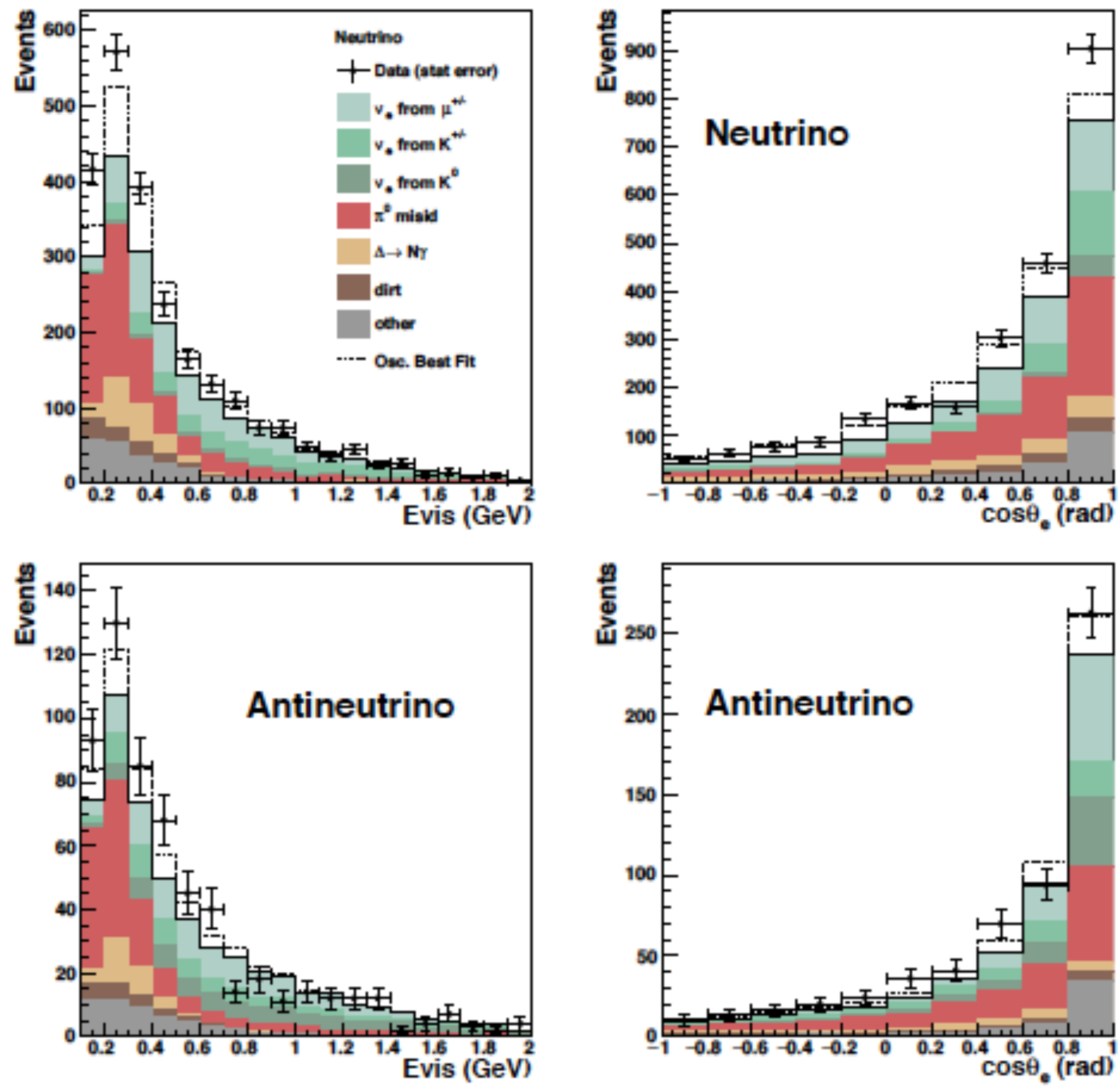
5. Alternative models?

Excess look like more photons (misID) than electrons
- peaked forward direction
- shape match with π^o spectrum

Any misID background missing?
- New NCγ process?
- New NCπ^o process?

or BSM physics?
- BSM γ production process?
- BSM e-scattering process?
- BSM oscillation physics?

(see next talk)



Future of MiniBooNE

MiniBooNE run will be end on June 2019
- Expected to reach ~ 18E20POT in ν-mode
- The excess may reach ~ 5σ

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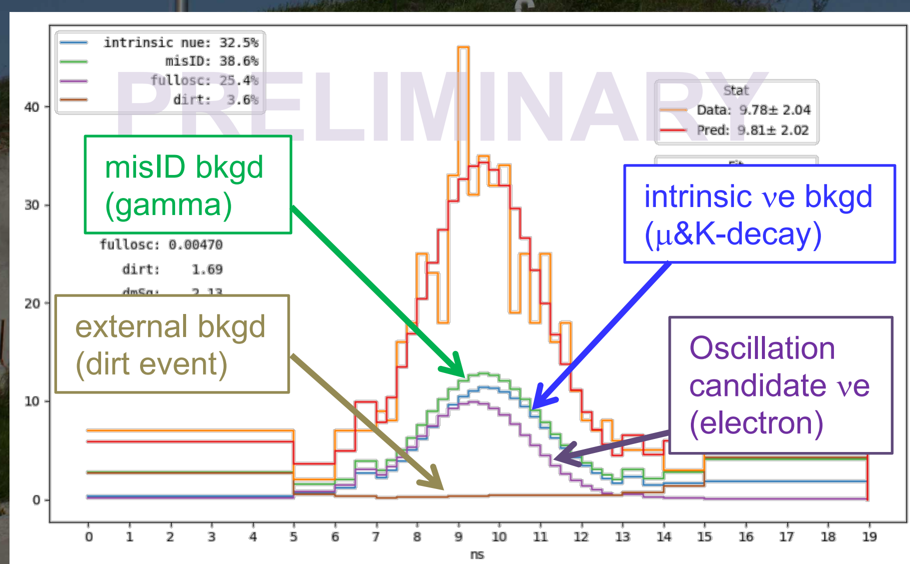
Next oscillation analysis: timing background rejection
- It is possible to reject both intrinsic and misID backgrounds by timing (ongoing)

Bunch timing structure, data-MC comparison
- intrinsic bkgd: μ-decay ν_e, K-decay ν_e → slow
- misID bkgd: photon conversion → slow



Conclusion

MiniBooNE is a short-baseline neutrino oscillation experiment

After 15 years of running
- neutrino mode: 381.2 $\pm$ 85.2 excess (4.5σ)
- antineutrino mode: 79.3 $\pm$ 28.6 excess (2.8σ)

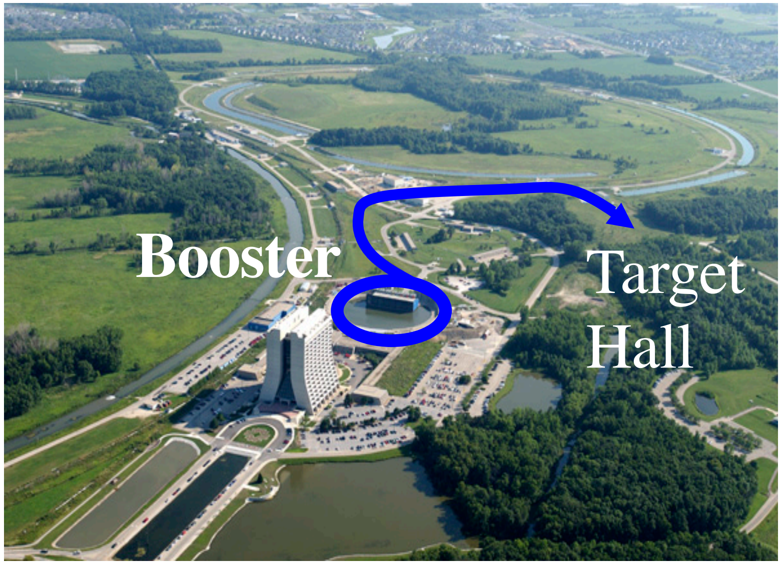
MiniBooNE has many legacies in this community
- Many useful tools
- Many useful people
- Many new topics in nuclear physics

But the biggest legacy is the short-baseline anomaly

Thank you for your attention!

backup

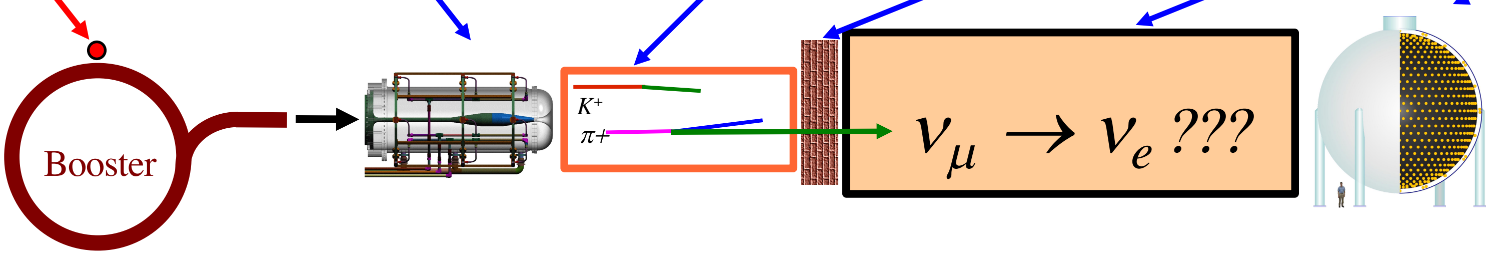
2. Neutrino beam



MiniBooNE extracts beam from the 8 GeV Booster

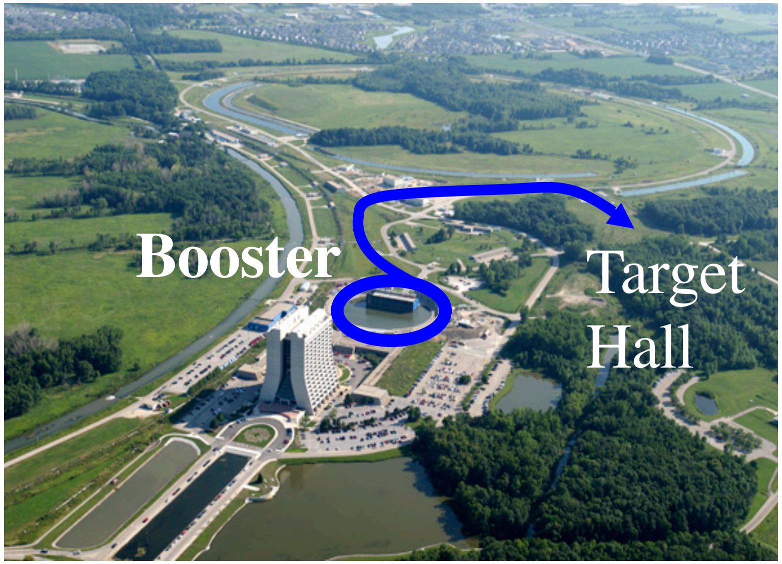
FNAL Booster

FNAL Booster | target and horn | decay region | absorber | dirt | detector



primary beam (protons) → secondary beam (mesons) → tertiary beam (neutrinos)

2. Neutrino beam



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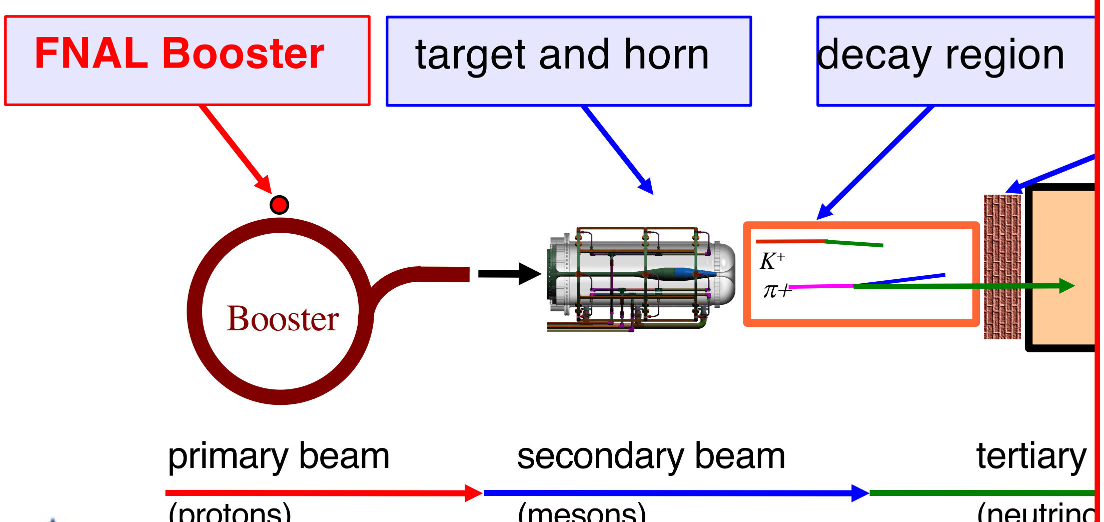
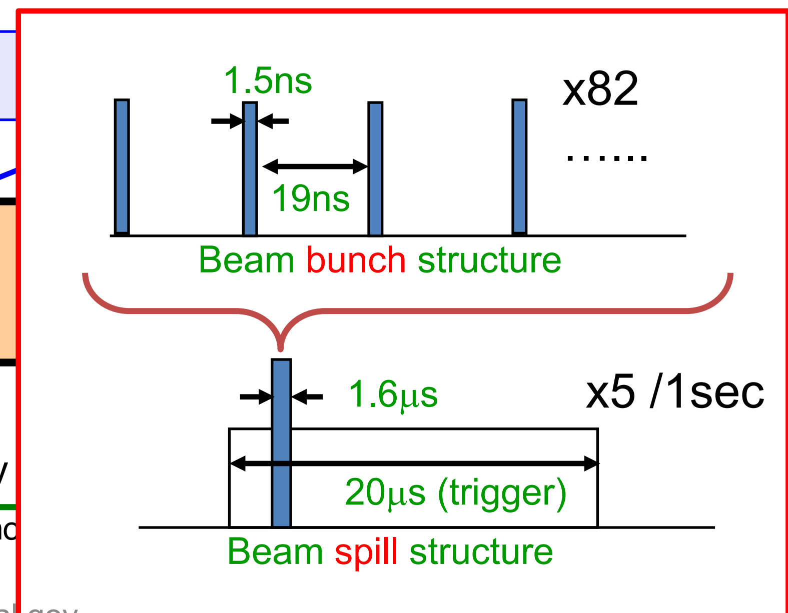
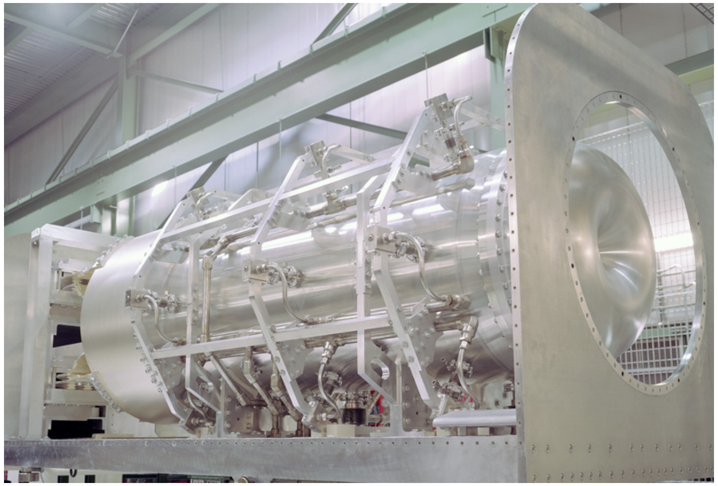




2. Neutrino beam

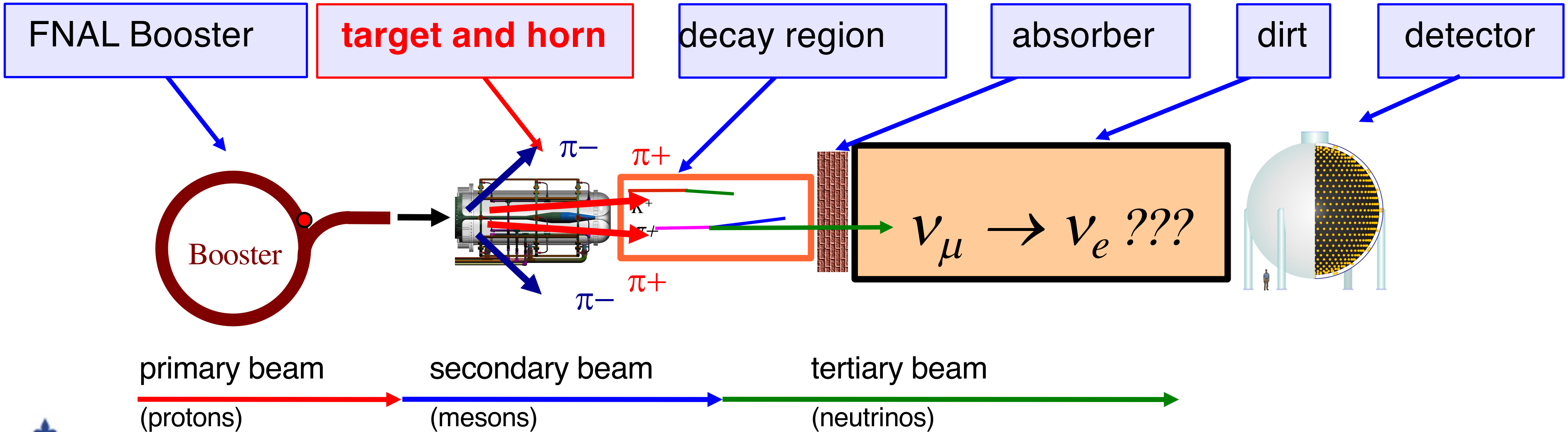
Magnetic focusing horn



8GeV protons are delivered to a 1.7 λ Be target

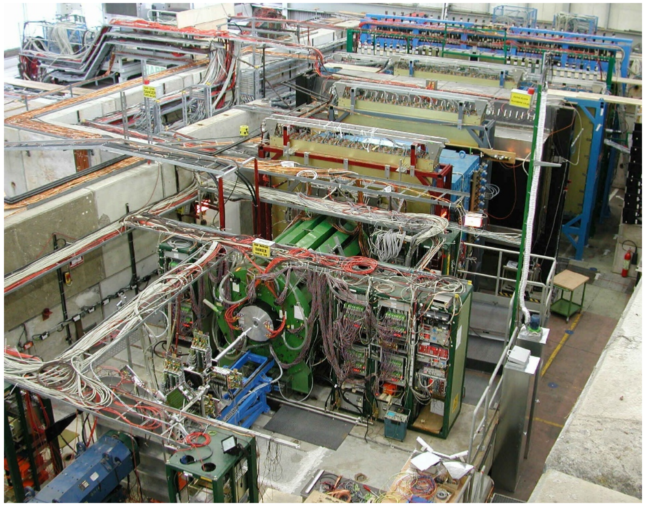
within a magnetic horn (2.5 kV, 174 kA) that increases the flux by $\times$ 6

By switching the current direction, the horn can focus either positive (neutrino mode) or negative (antineutrino mode) mesons.



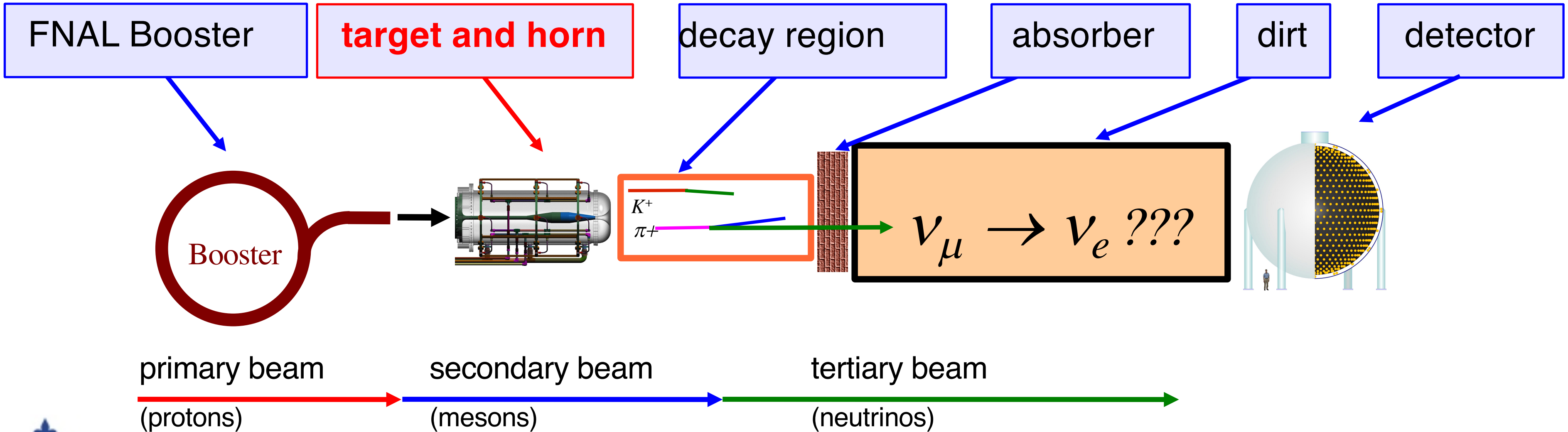
2. Neutrino beam

HARP experiment (CERN)



Modeling of meson production is based on the measurement done by HARP collaboration.

- Identical, but 5% λ Beryllium target
- 8.9 GeV/c proton beam momentum
- >80% coverage for $\pi+$



MiniBooNE, PRD79(2009)072002
HARP, Eur.Phys.J.C52(2007)29

2. Neutrino beam

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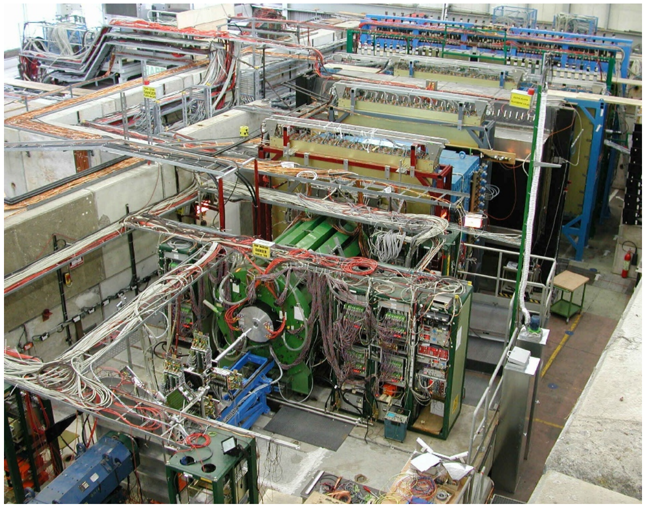

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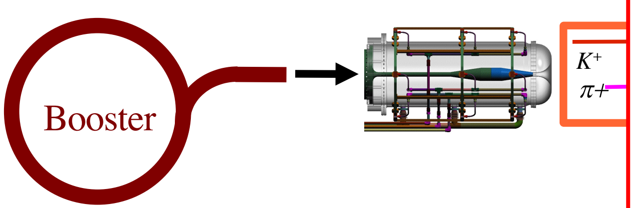
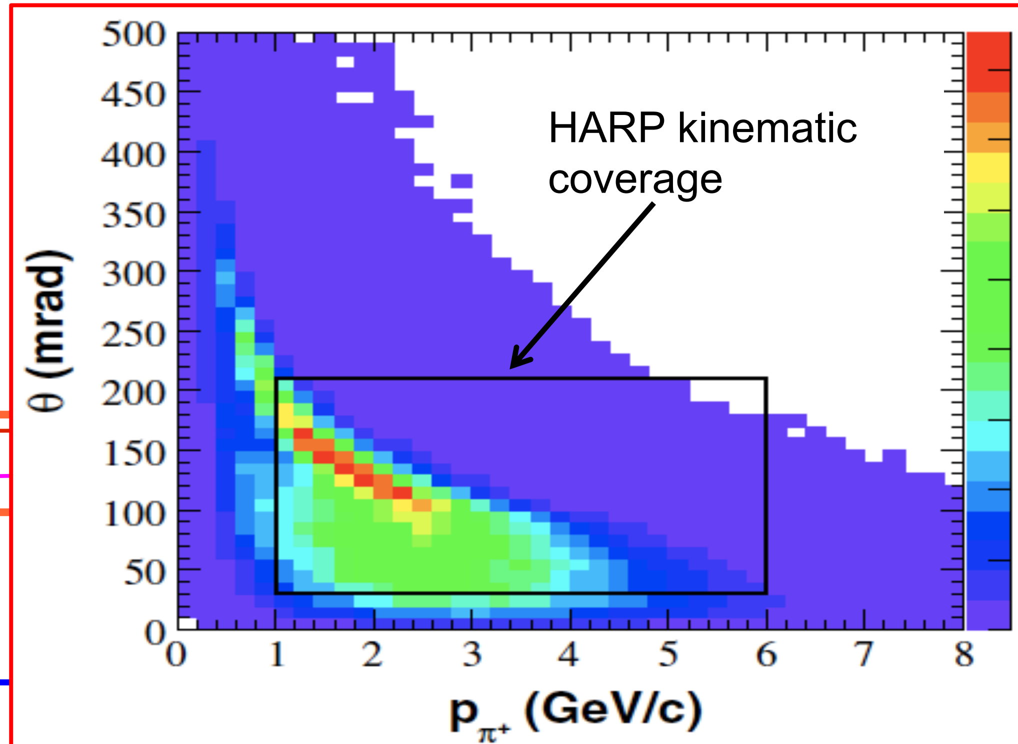
FNAL Booster

target and horn



primary beam
(protons)

secondary beam
(mesons)



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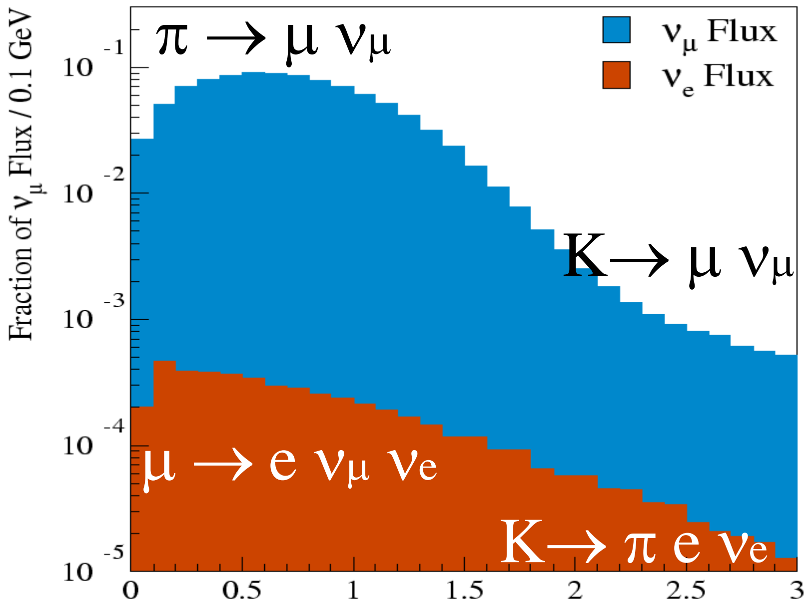
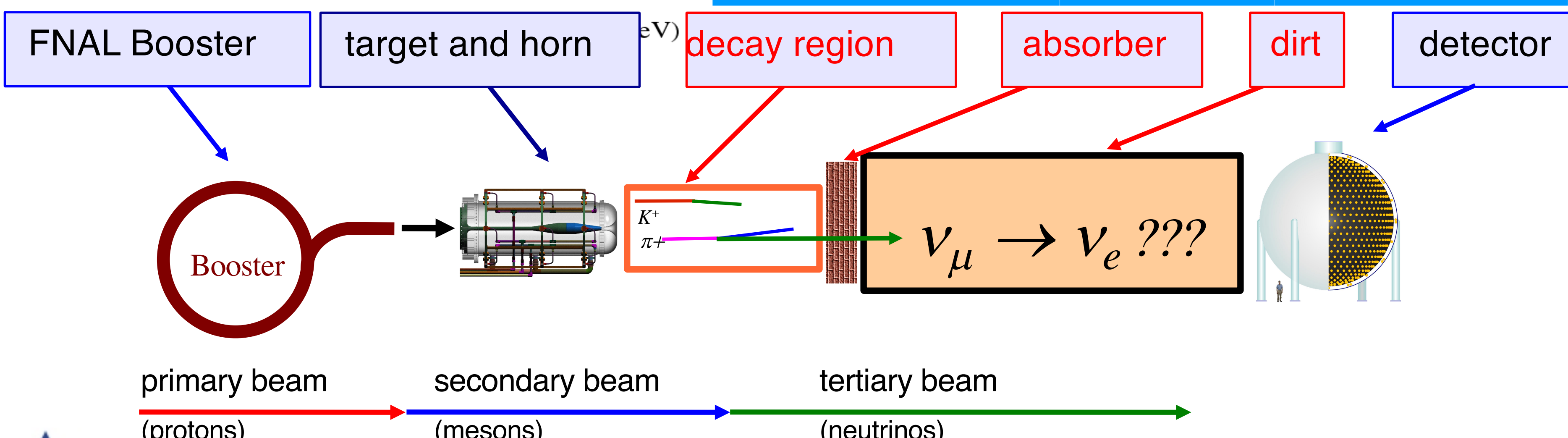


Neutrino flux from simulation by GEANT4

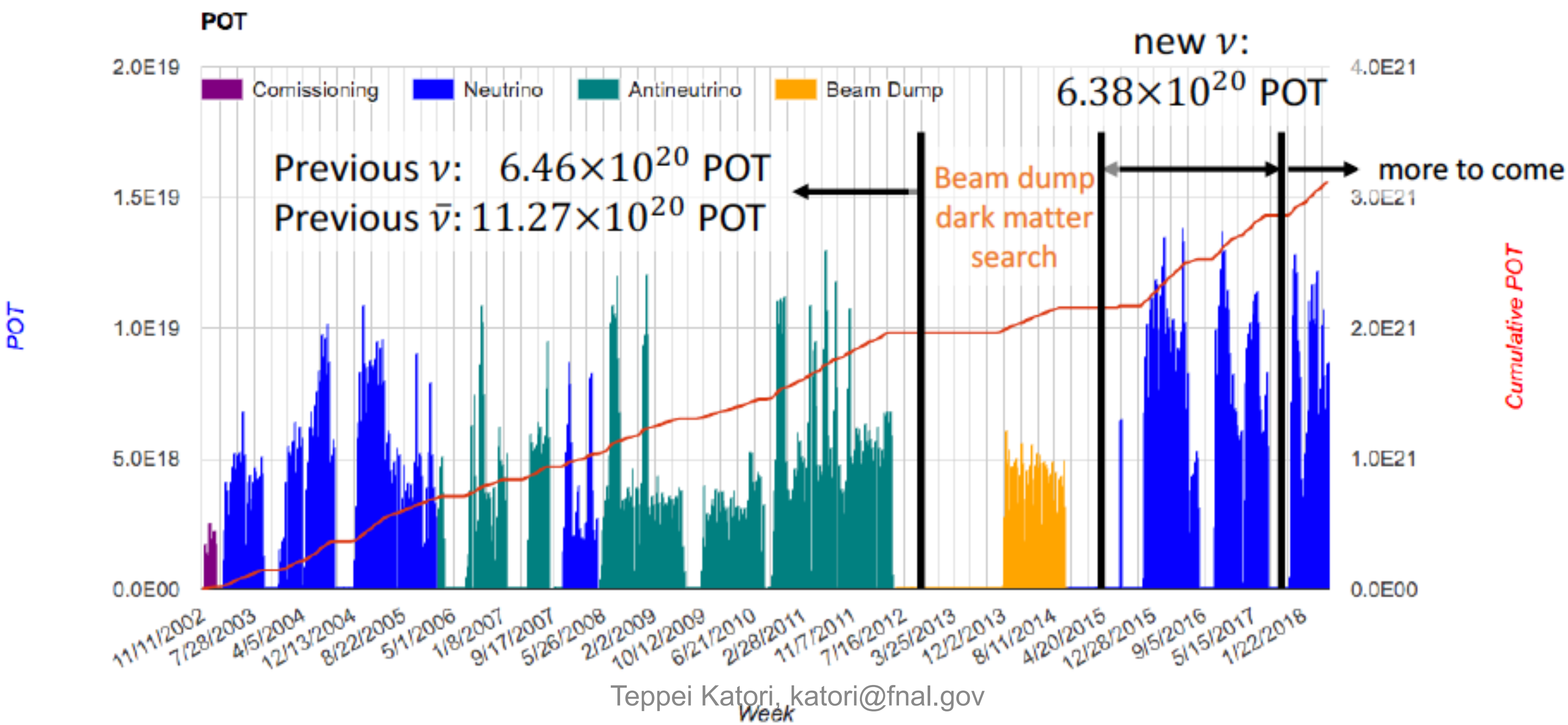
MiniBooNE is the ν_e (anti ν_e) appearance oscillation experiment, so we need to know the distribution of beam origin ν_e and anti ν_e (intrinsic ν_e)

	neutrino mode	antineutrino mode
intrinsic ν_e contamination	0.6%	0.6%
intrinsic ν_e from μ decay	49%	55%
intrinsic ν_e from K decay	47%	41%
others	4%	4%
wrong sign fraction	6%	16%

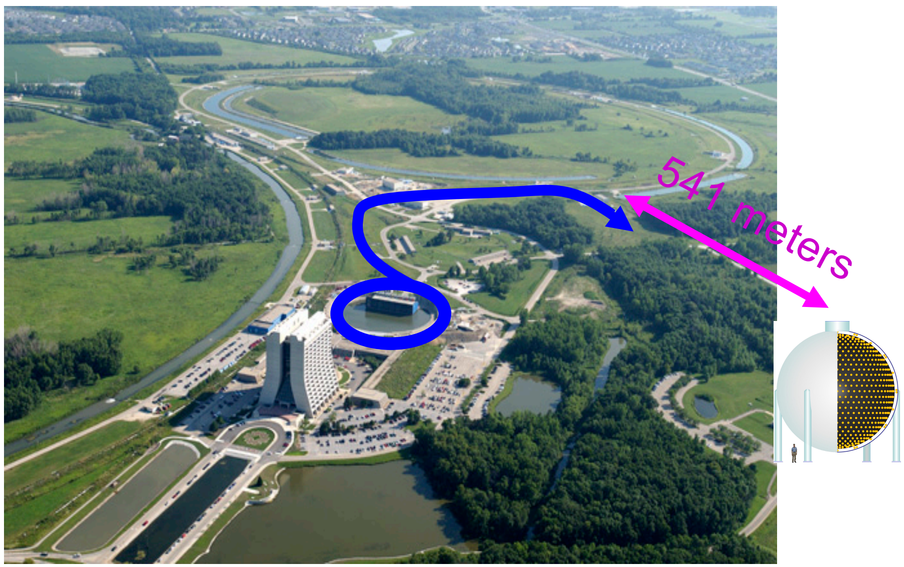


3. Data taking

- 15+ years of running in neutrino, antineutrino, and beam dump mode. More than 30×10^{20} POT to date.
- Result of a combined 12.84×10^{20} POT in ν mode + 11.27×10^{20} POT in $\bar{\nu}$ mode is presented in this talk



3. Events in the Detector



The MiniBooNE Detector

- 541 meters downstream of target
- 12 meter diameter sphere

  (10 meter “fiducial” volume)
- Filled with 800 t of pure mineral oil (CH_2)

  (Fiducial volume: 450 t)
- 1280 inner phototubes,
- 240 veto phototubes

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MiniBooNE,NIM.A599(2009)28

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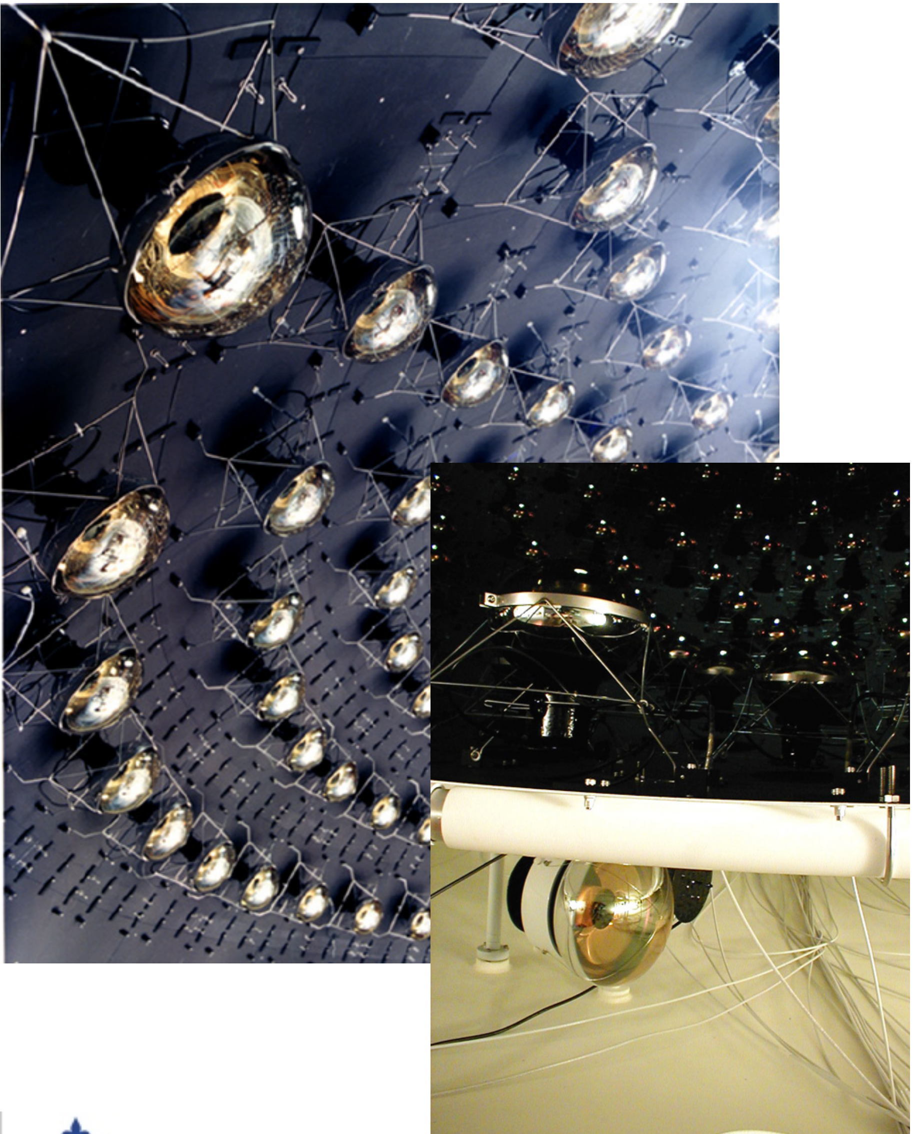

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Times of hit-clusters (subevents)

Beam spill (1.6μs) is clearly evident

simple cuts eliminate cosmic backgrounds

Neutrino Candidate Cuts

<6 veto PMT hits

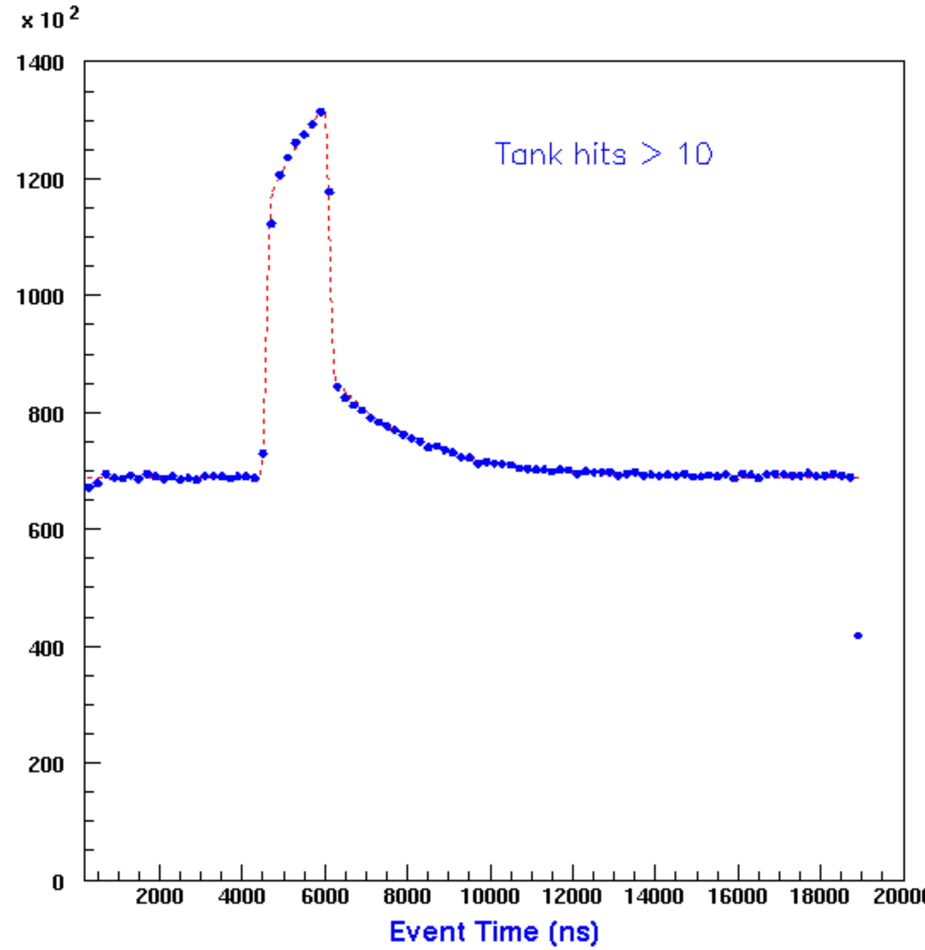
Gets rid of muons

>200 tank PMT hits

Gets rid of Michels

Only neutrinos are left!

Beam and Cosmic BG



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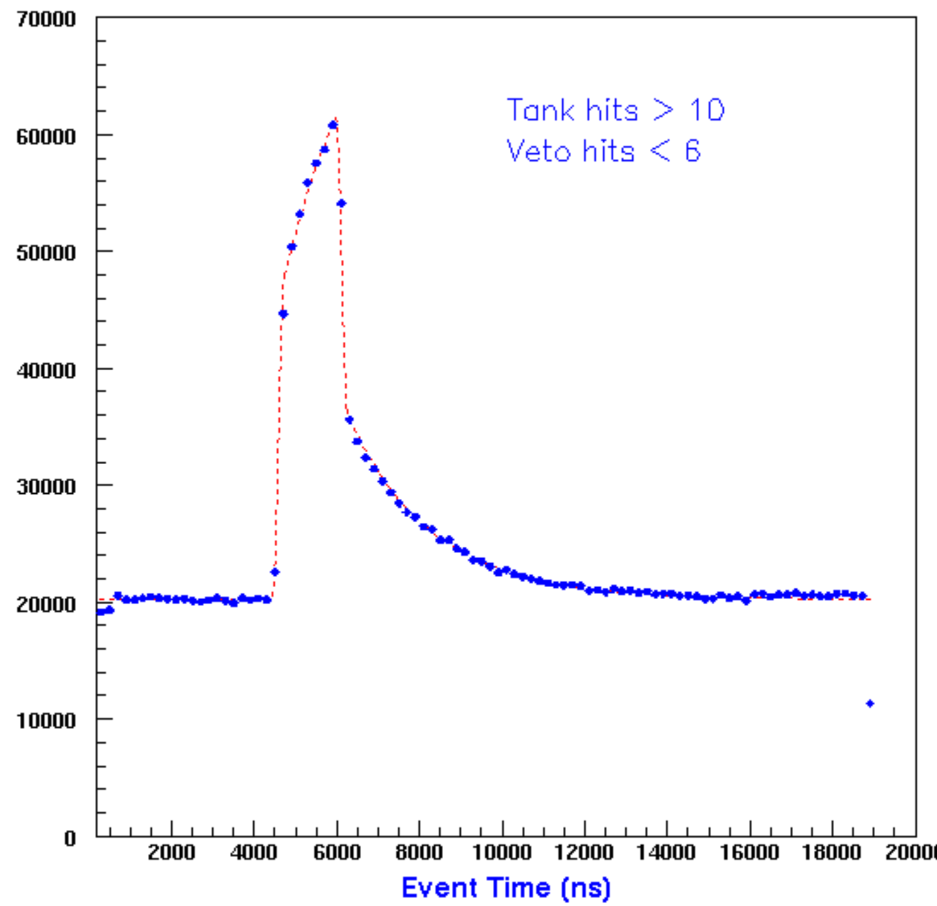

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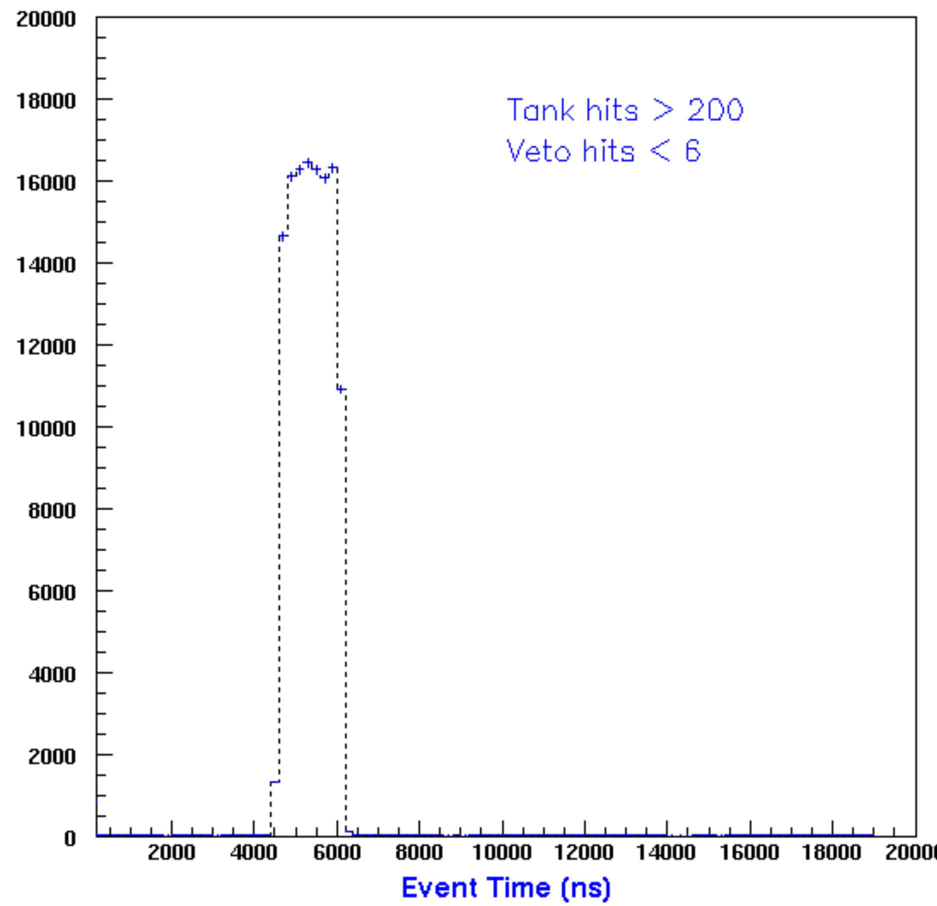
Beam Only



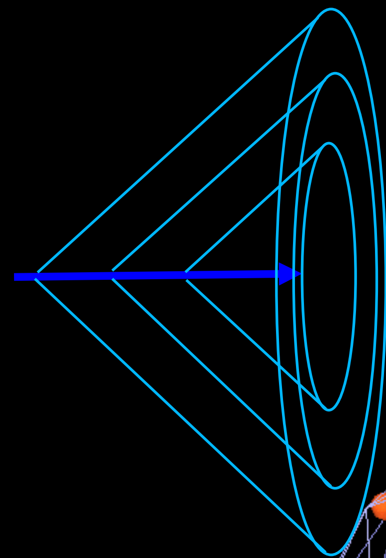
3. Events in the Detector

MiniBooNE collaboration, NIM.A599(2009)28

Muons

- Long strait tracks

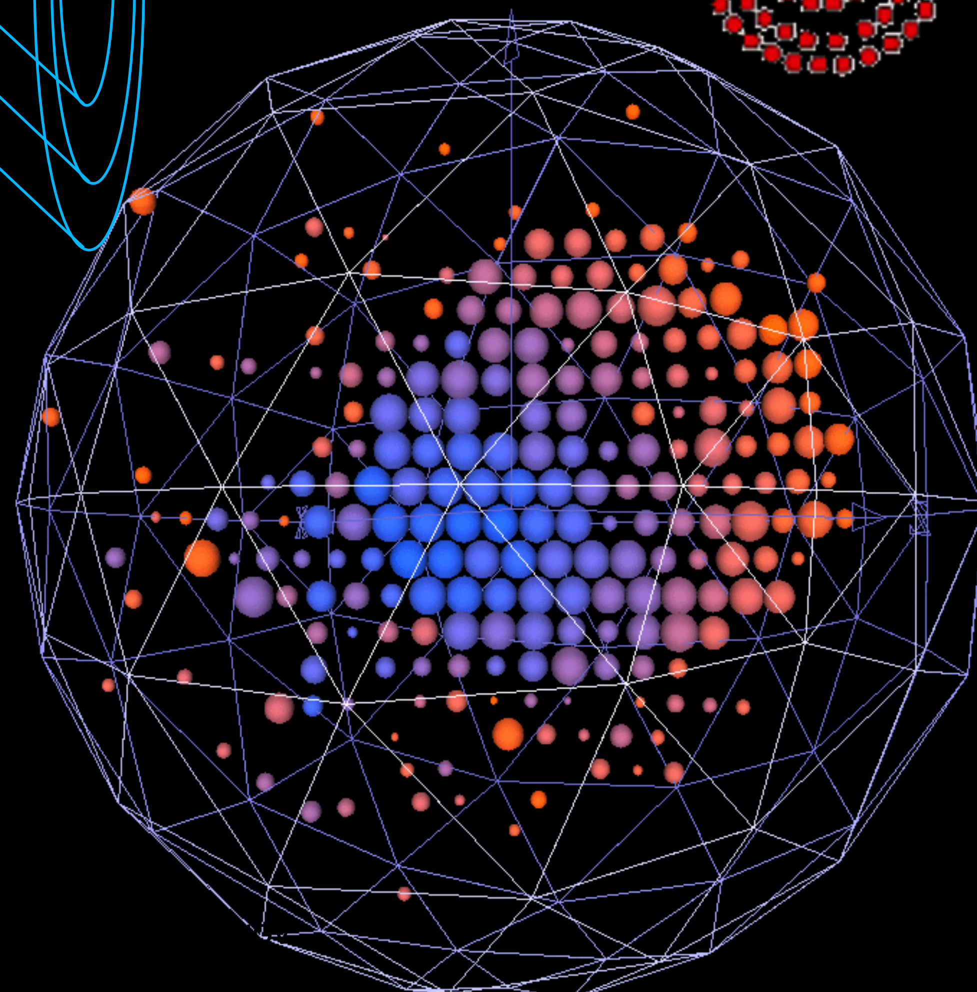
→ Sharp clear rings



Electrons

- Multiple scattering
- Radiative processes

→ Scattered fuzzy rings



Neutral pions

- Decays to 2 photons

→ Double fuzzy rings

NC elastic scattering

- No Cherenkov radiation

→ Isotropic scintillation hits

3. Events in the Detector

MiniBooNE collaboration,
NIM.A599(2009)28

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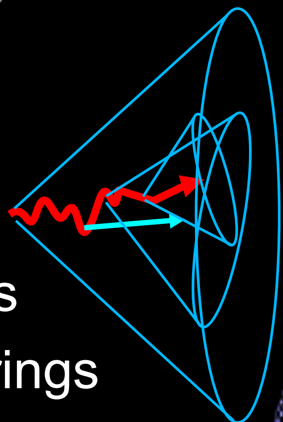

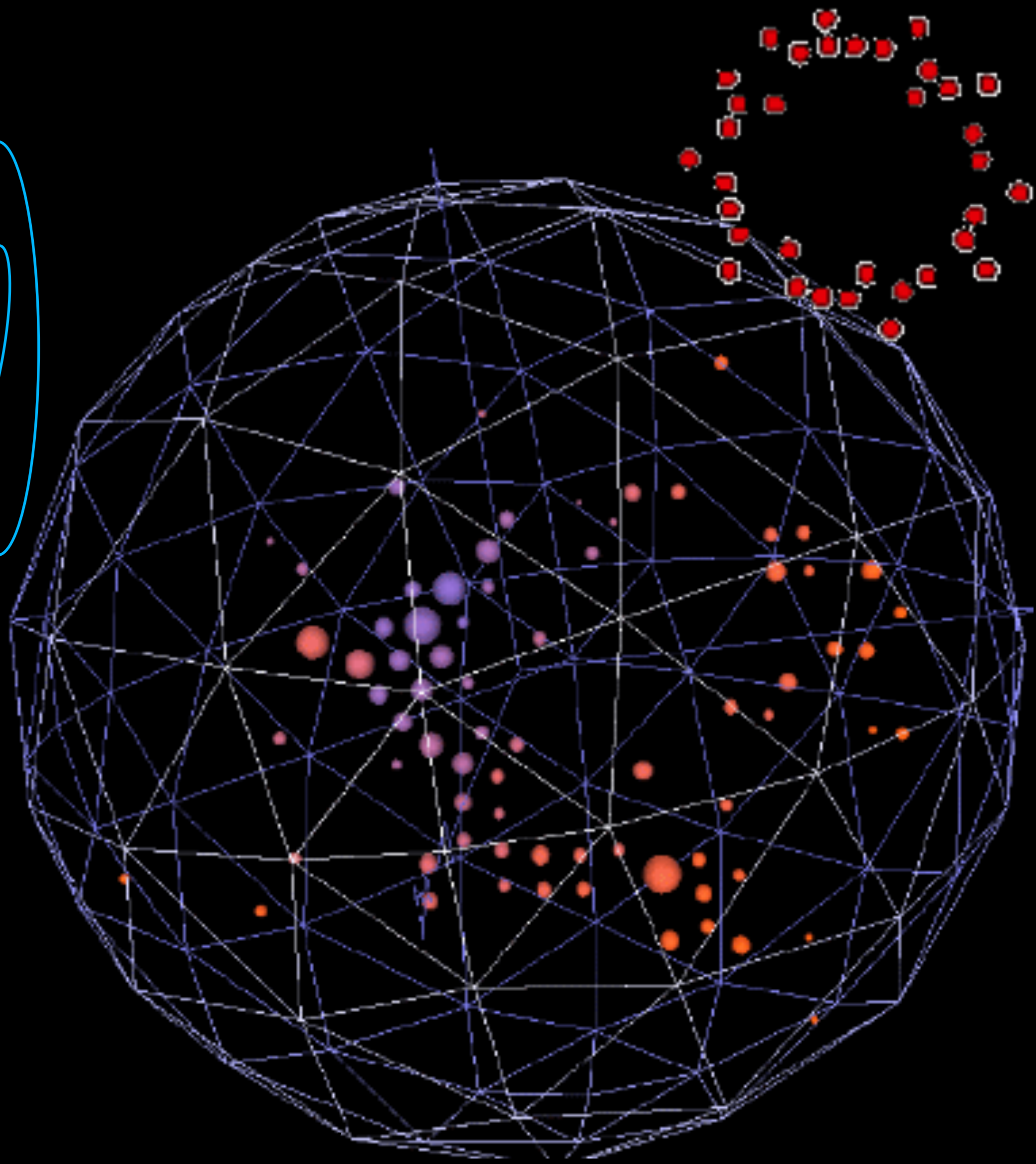

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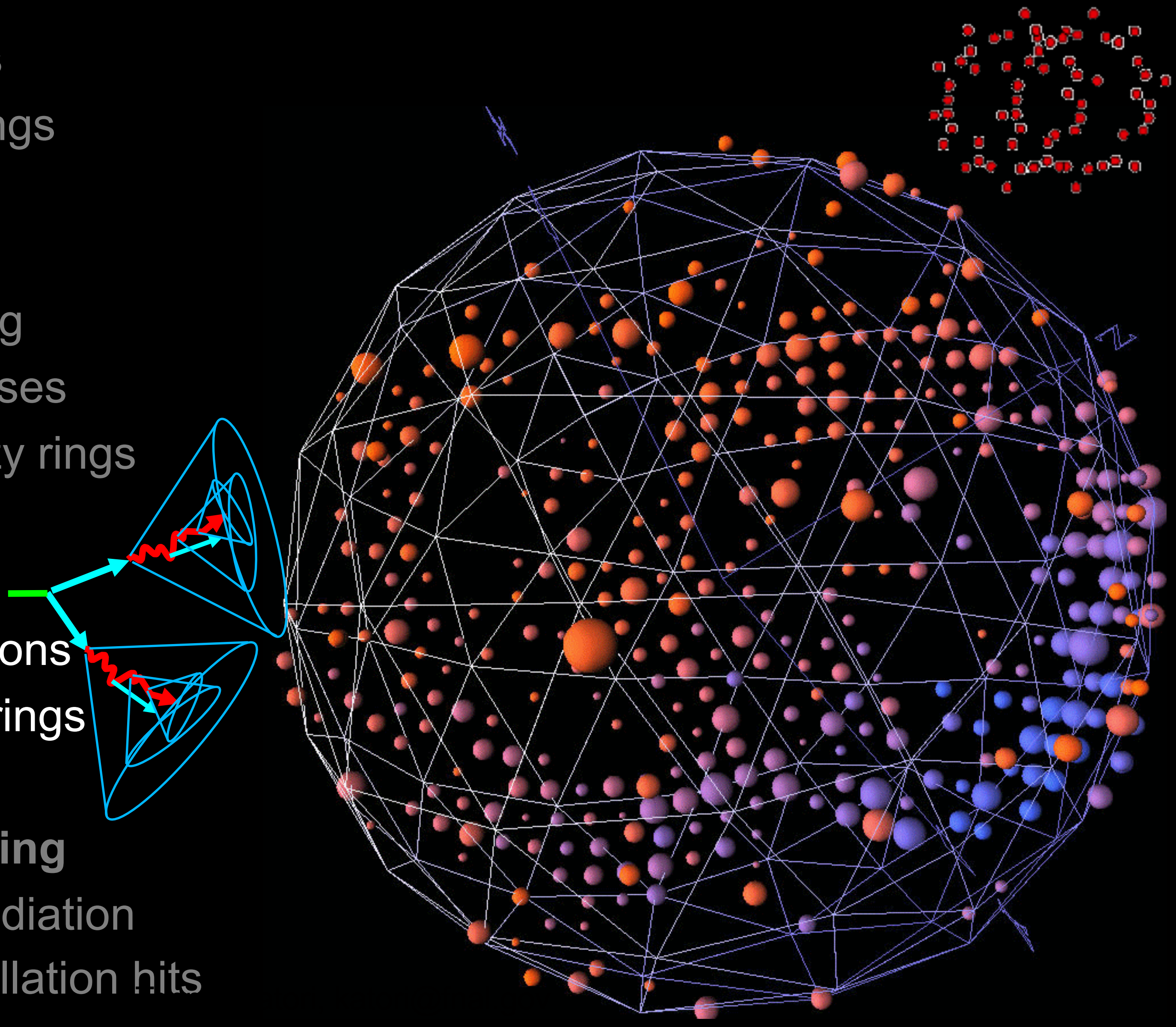

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NIM.A599(2009)28

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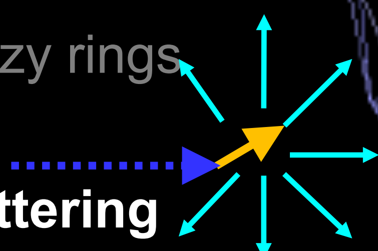

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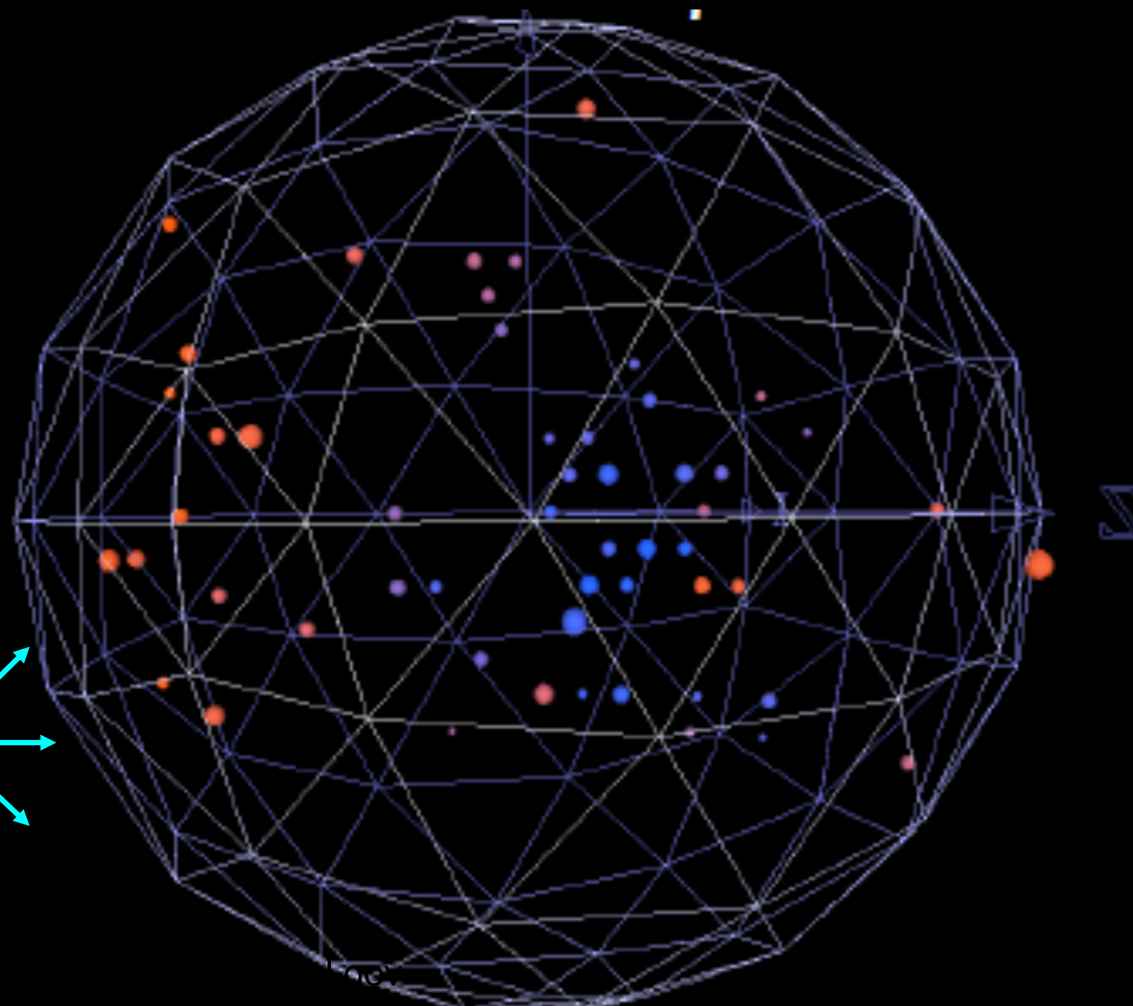


MiniBooNE: PRL100(2008)032301

3. QE kinematics based energy reconstruction

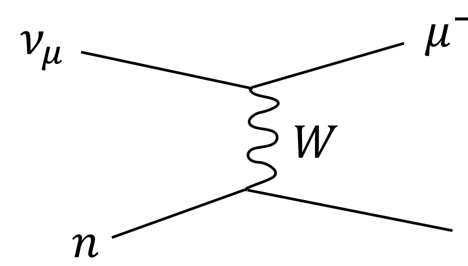
Event reconstruction from Cherenkov ring profile for PID

- scattering angle θ and kinetic energy of charged lepton T are measured

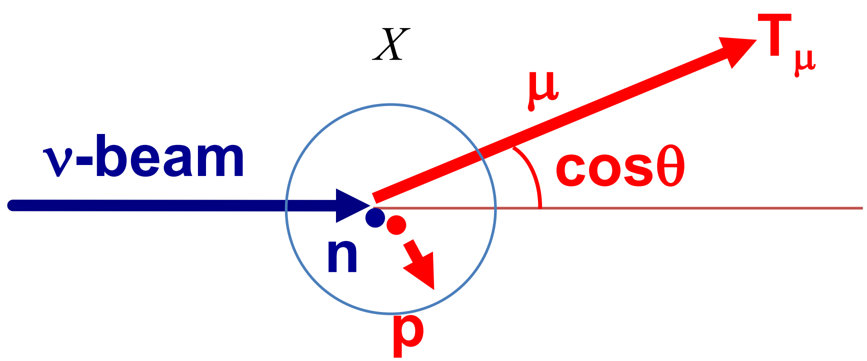
Charged Current Quasi-Elastic (CCQE) interaction

The simplest and the most abundant interaction around ~1 GeV. Neutrino energy is reconstructed from the observed lepton kinematics "QE assumption"

1. assuming neutron at rest
2. assuming interaction is CCQE



$$\nu_\mu + n \longrightarrow p + \mu^- \ (\nu_\mu + X \longrightarrow X' + \mu^-)$$



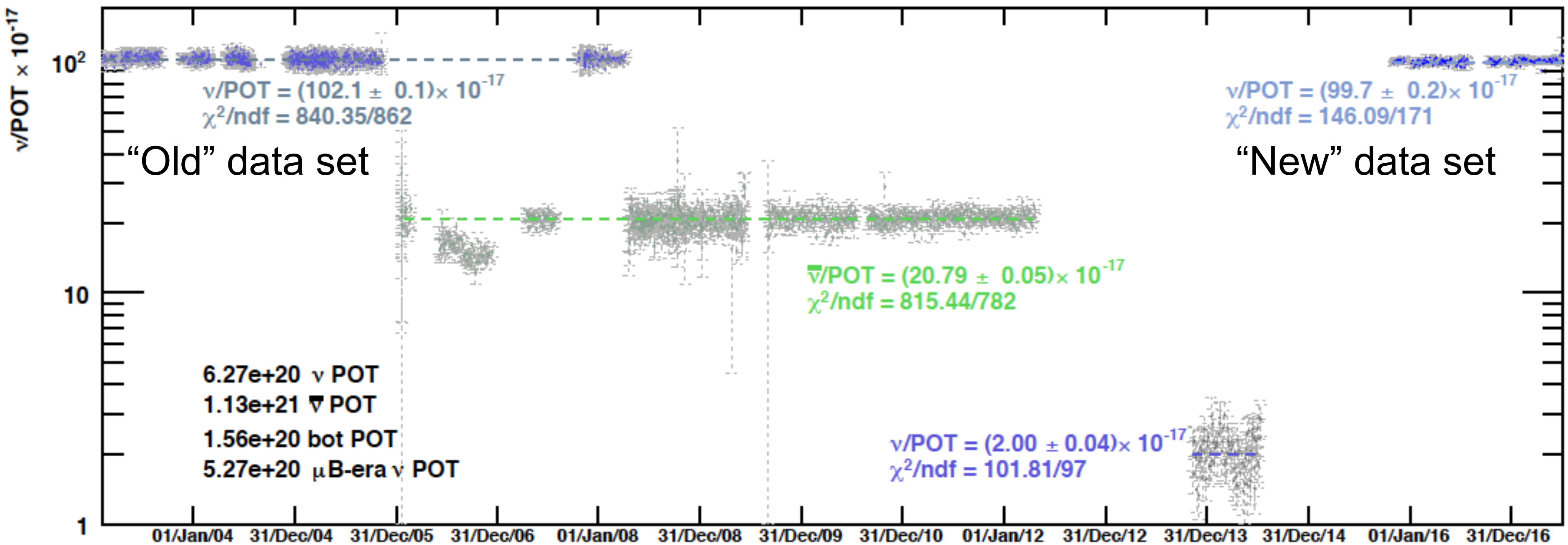
$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

CCQE is the most important channel of neutrino oscillation physics for MiniBooNE, T2K, microBoonE, SBND, etc (also important for NOvA, Hyper-Kamiokande, DUNE, etc)

3. Detector stability

Event rate look consistent from expectations
- Antineutrino mode (factor 5 lower event rate)
  - factor ~2 lower flux
  - factor ~2-3 lower cross section
- Dark matter mode (factor 50 lower event rate)
  - factor ~40 lower flux

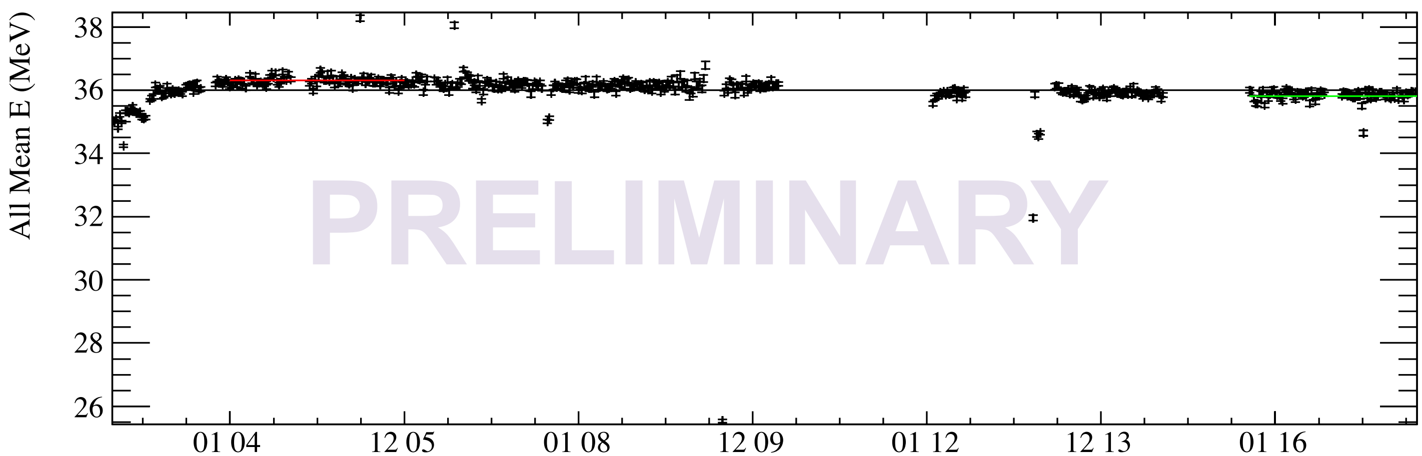
MiniBooNE, PRL118(2017)221803, PRD98(2018)112004



3. Detector stability

Old and new data agree within 2% over 8 years separation.

Michel electron spectrum peak



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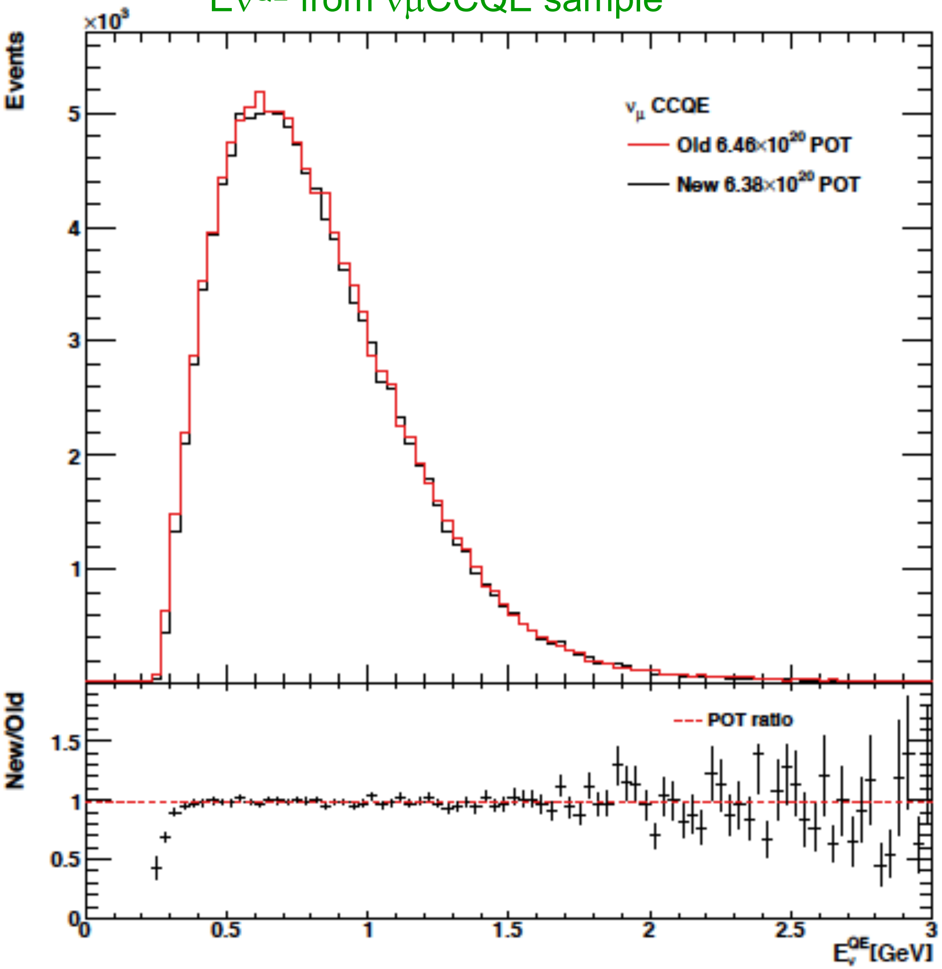
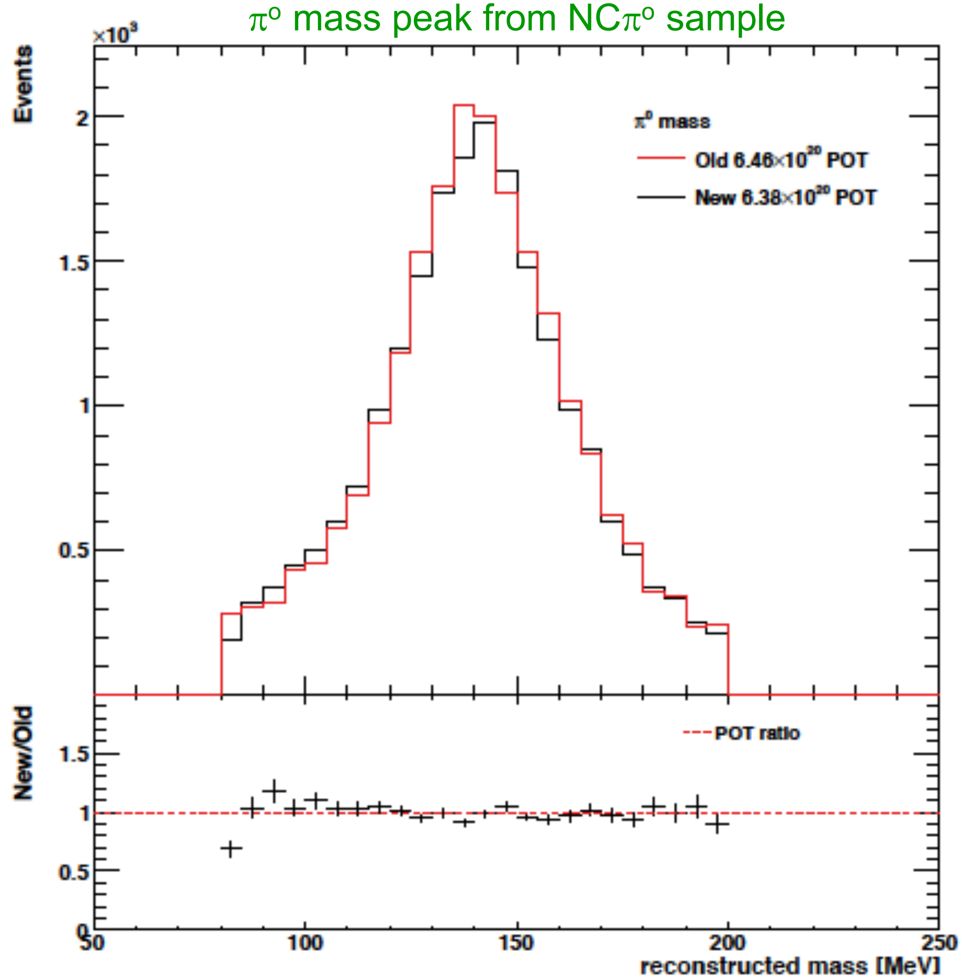
$E\nu^{QE}$ from $\nu\mu$CCQE sample



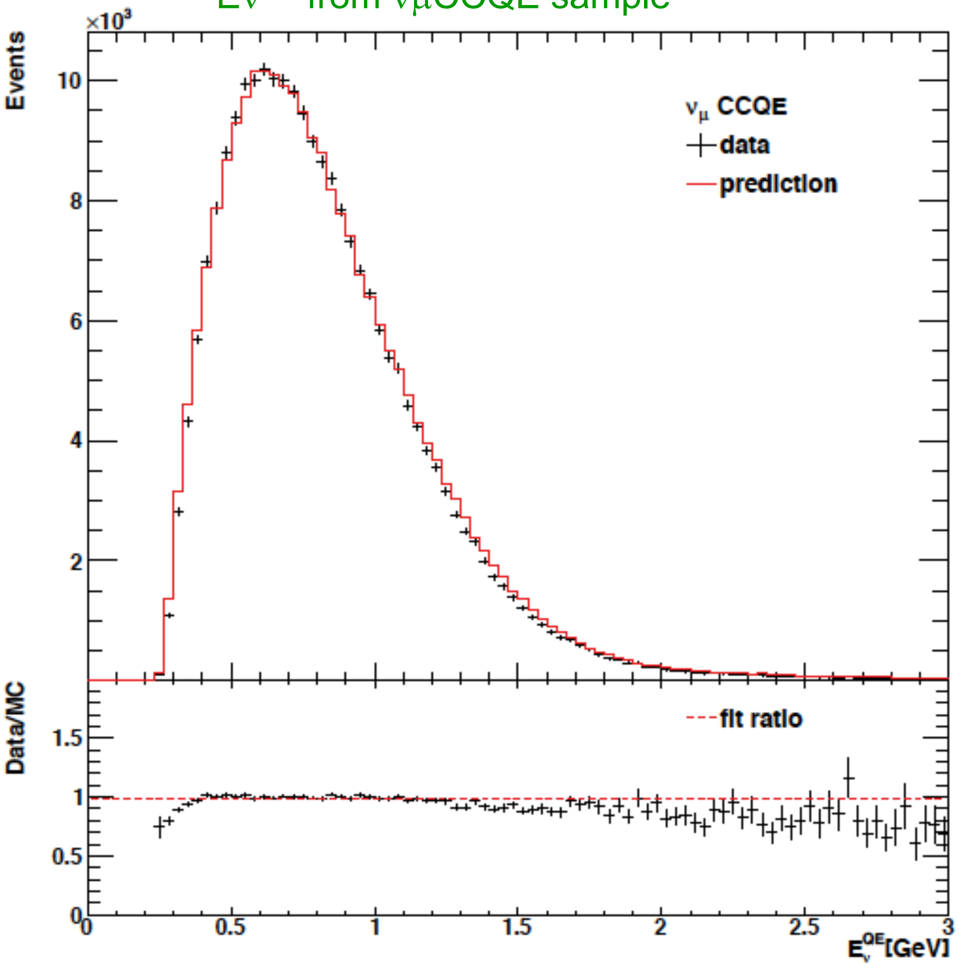
π^o mass peak from NCπ^o sample



3. Data-Simulation comparison

Old and new data agree within 2% over 8 years separation.
- Excellent agreements with MC.

$E\nu^{QE}$ from $\nu\mu$CCQE sample



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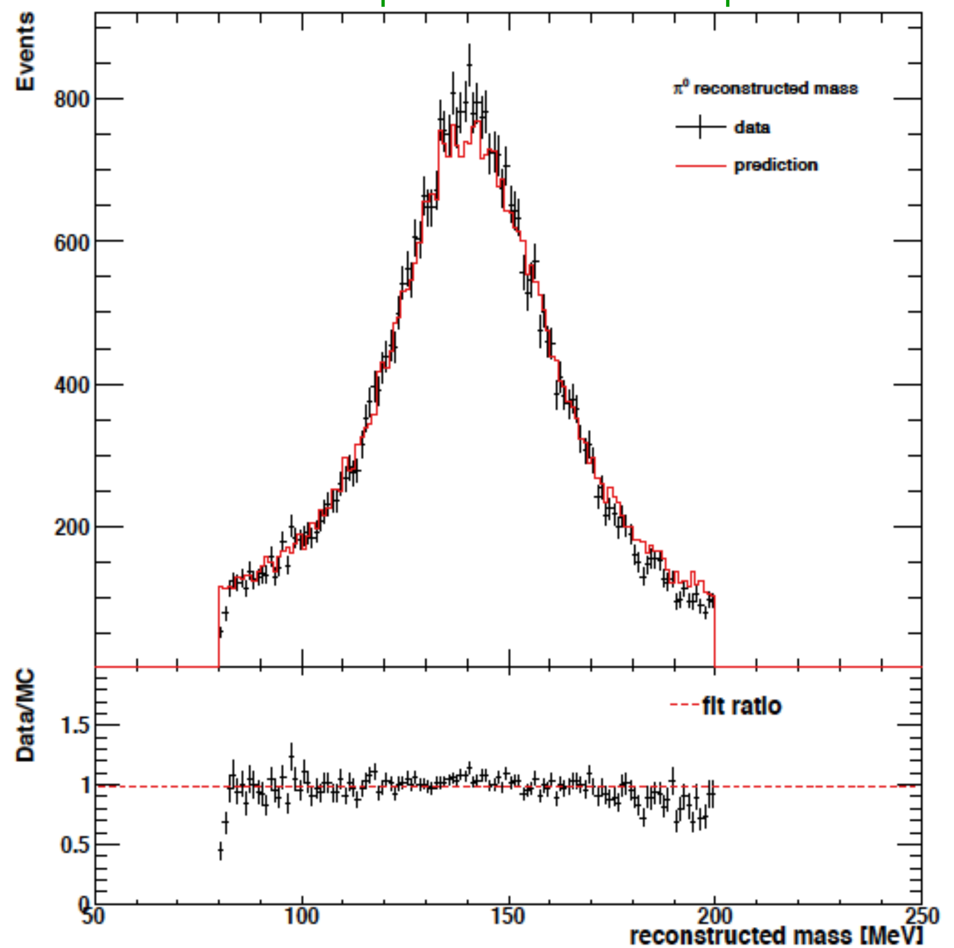
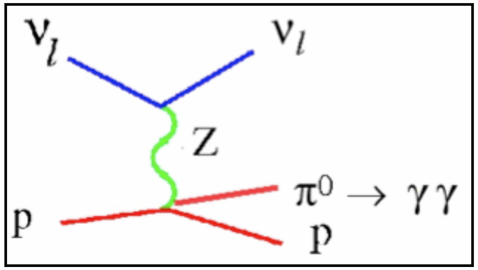
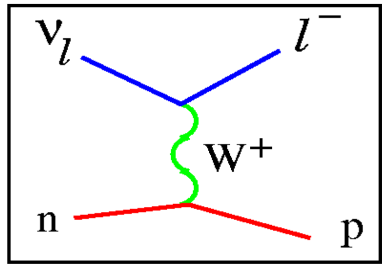
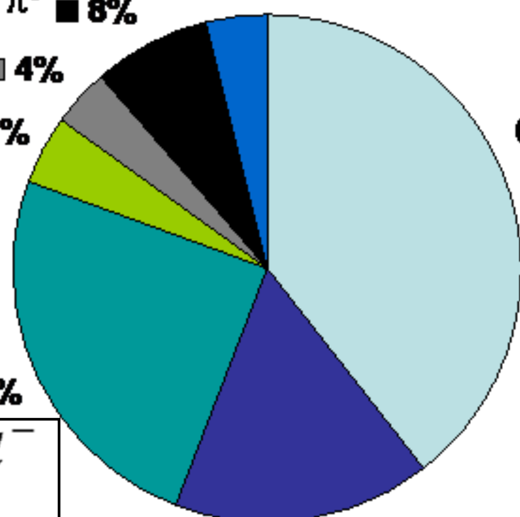
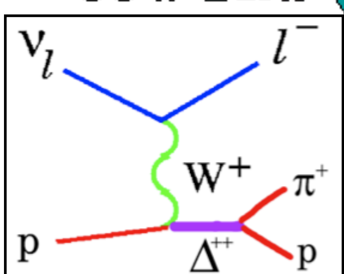


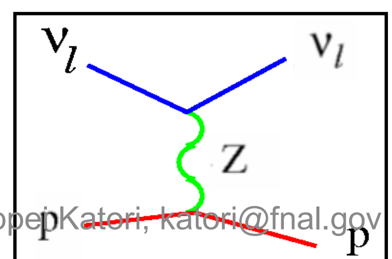
3. Cross section model





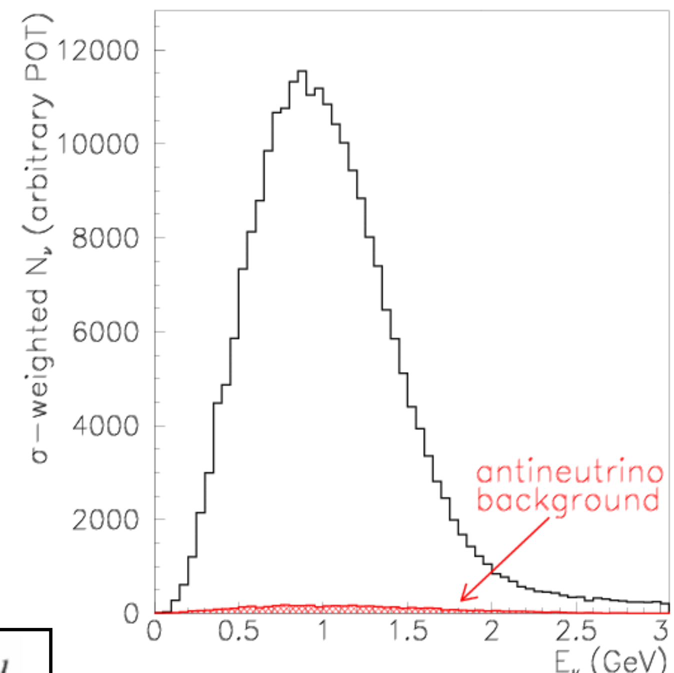






Predicted event rates before cuts (NUANCE Monte Carlo)

Casper, Nucl.Phys.Proc.Suppl.112(2002)161

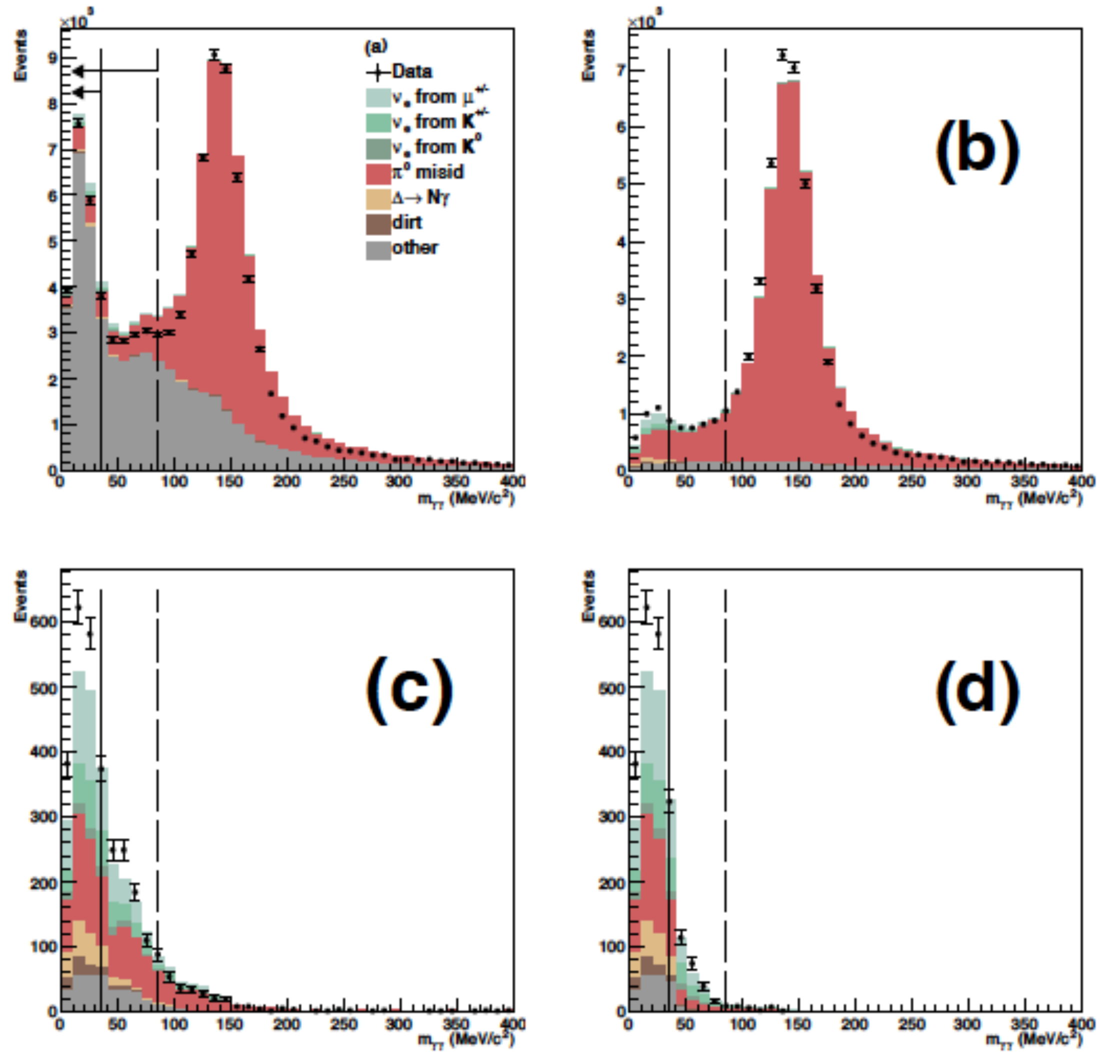


Event neutrino energy (GeV)

4. PID cuts Oscillation candidate events

4 PID cuts
(a) Before PID cuts
(b) After L(e/mu) cut
(c) After L(e/π^o) cut
(d) After $m_{\gamma\gamma}$ cut

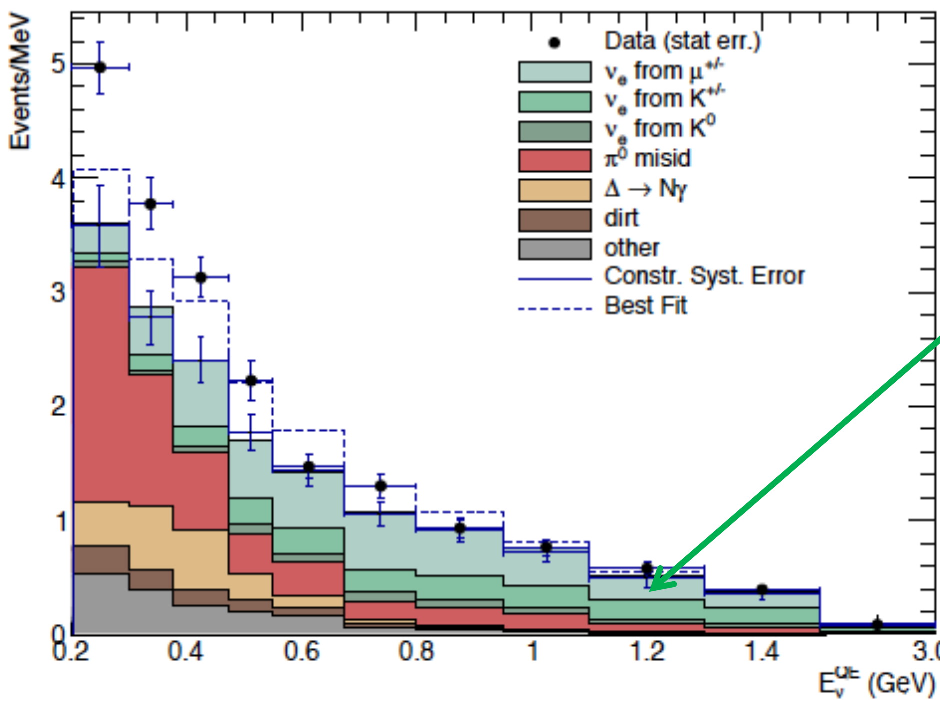
Old and new data agree within 2% over 8 years separation.



4. ν_e from μ-decay constraint

All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \to N\gamma$	172.5 ± 24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K^0_L Decay	54.5 ± 20.5	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0
Unconstrained Bkgd.	1590.5	398.2
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6



ν_e from μ decay is constrained from ν_μCCQE measurement

4. ν_e from μ-decay constraint

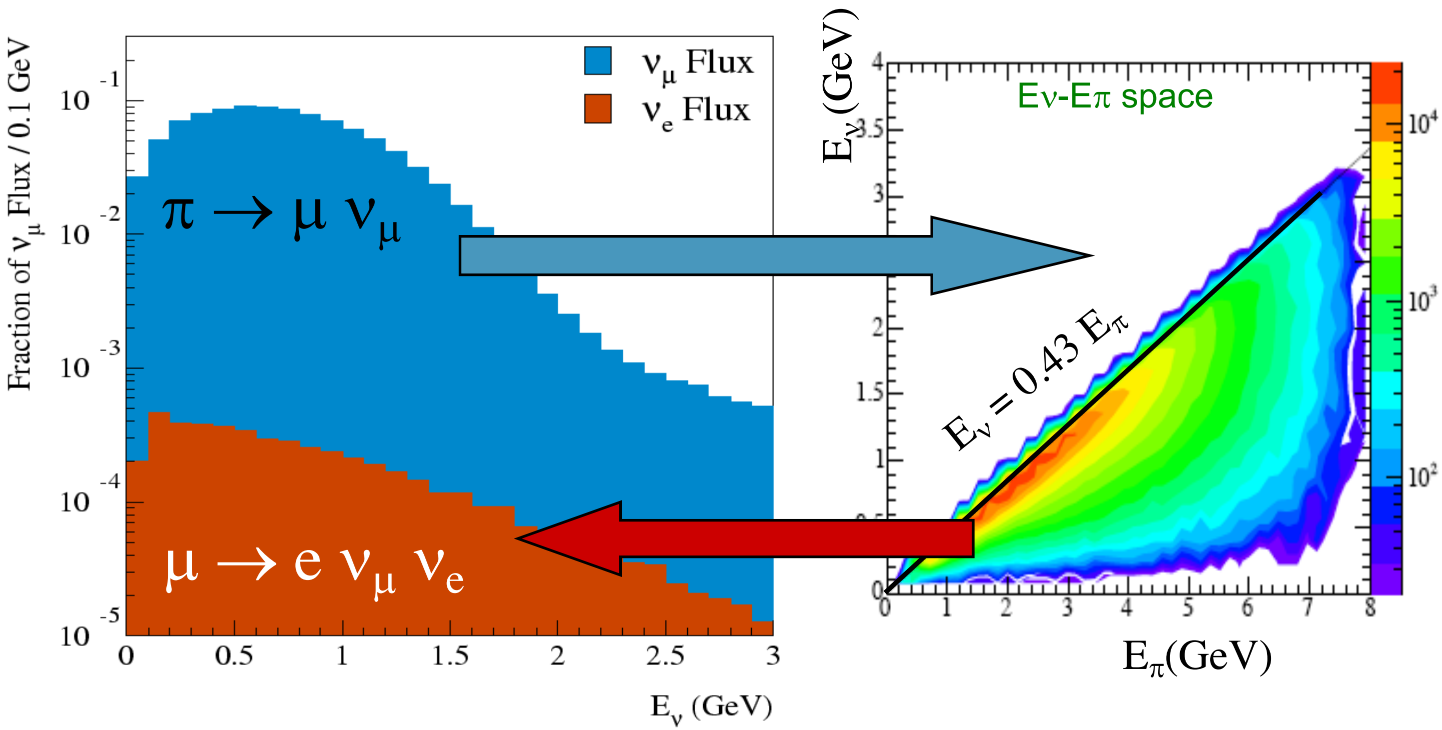
measured

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$
$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$
$$\mu^- \longrightarrow e^- + \nu_\mu + \bar{\nu}_e$$

guessed

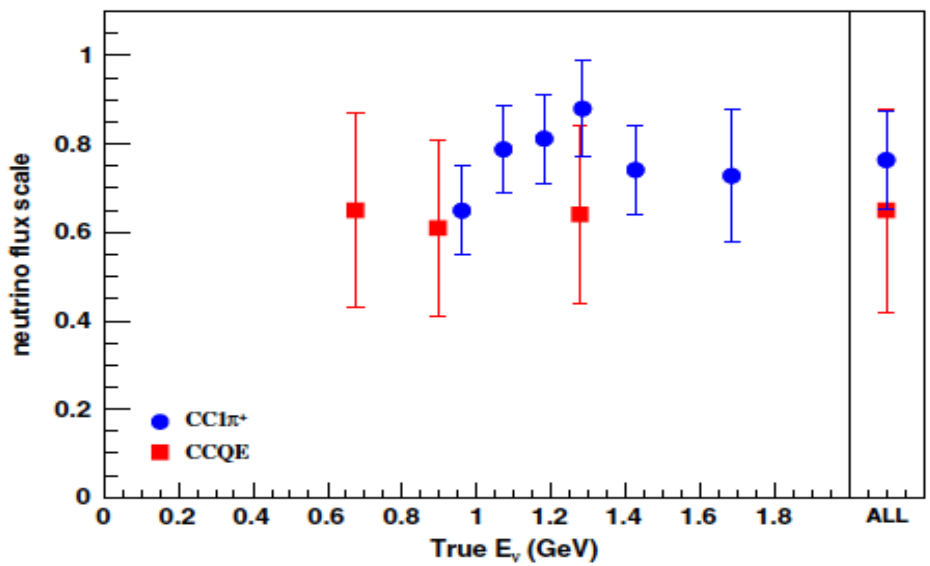
All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E

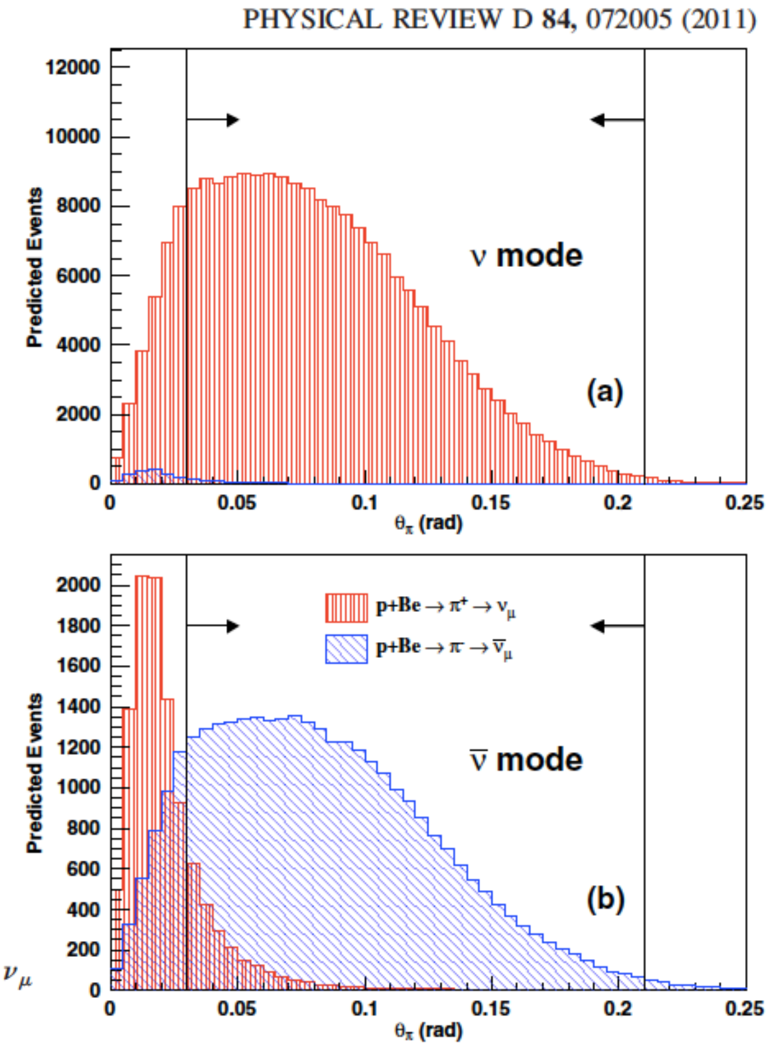
They are large background, but we have a good control of $\nu_e \& \bar{\nu}_e$ background by joint $\nu_e \& \nu_\mu (\bar{\nu}_e \& \bar{\nu}_\mu)$ fit for oscillation search.



4. Anti-neutrino mode flux tuning

$\bar{\nu}_e \& \bar{\nu}_\mu$ flux are harder to predict due to larger wrong sign ($\nu_e \& \nu_\mu$) background, and measured lepton kinematics and π^+ production are used to tune flux
→ they consistently suggest we overestimate antineutrino flux around 20%





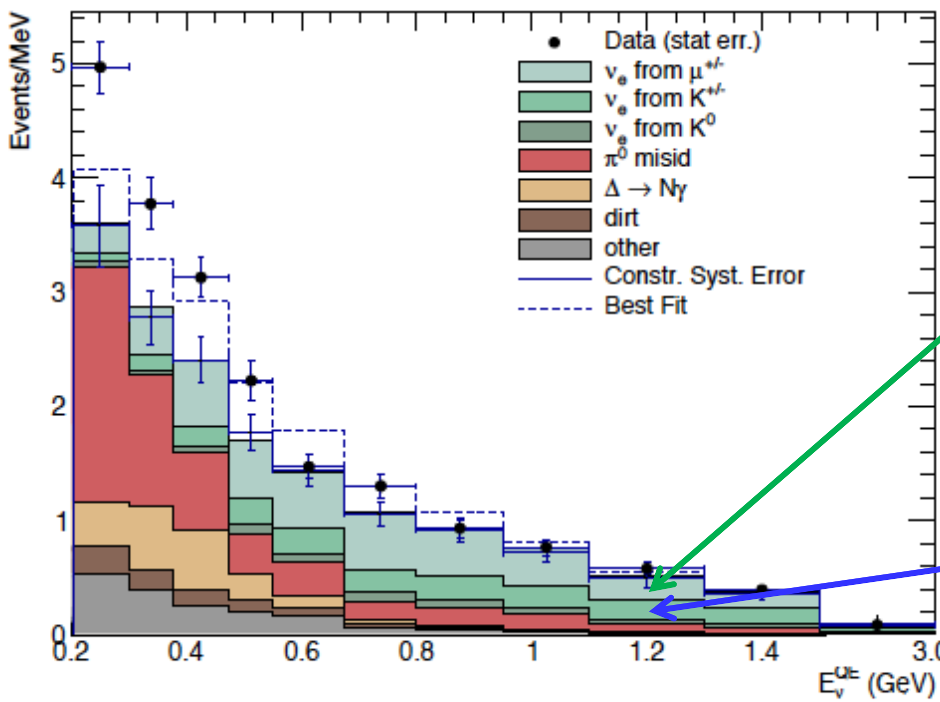
Michel electron counting is sensitive to ν_μ contamination in $\bar{\nu}_\mu$ beam

$$
\begin{aligned}
1:&\quad \nu_\mu + p(n) \rightarrow \mu^- + p(n) + \pi^+ \hookrightarrow \mu^+ + \nu_\mu \\
2:&\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu \\
3:&\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu.
\end{aligned}
$$

4. ν_e from K^+-decay constraint

All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \rightarrow N\gamma$	172.5 ± 24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K^0_L Decay	54.5 ± 20.5	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0
Unconstrained Bkgd.	1590.5	398.2
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6

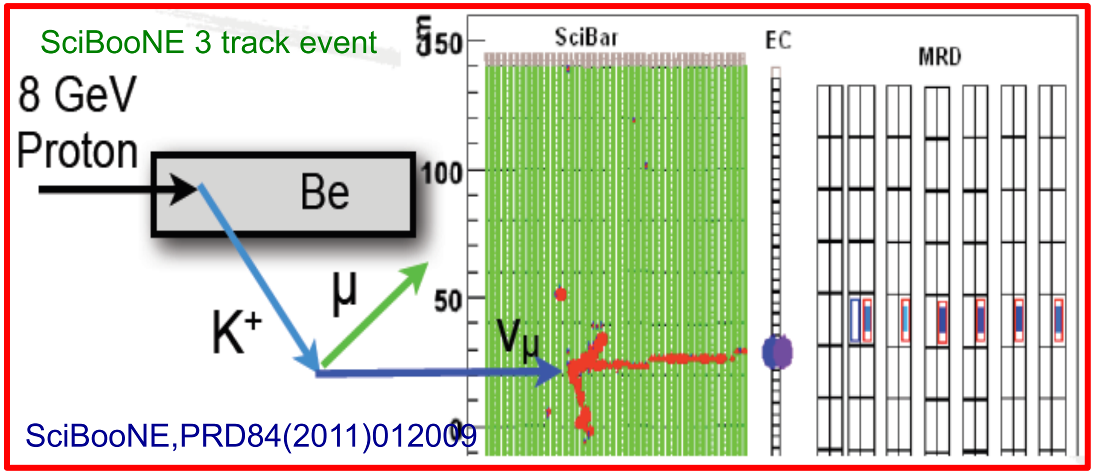


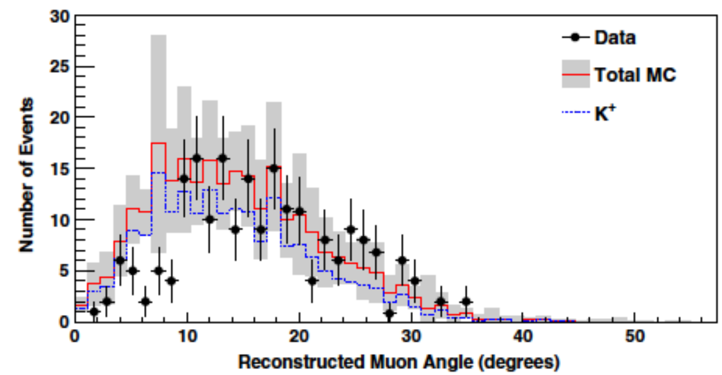
ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

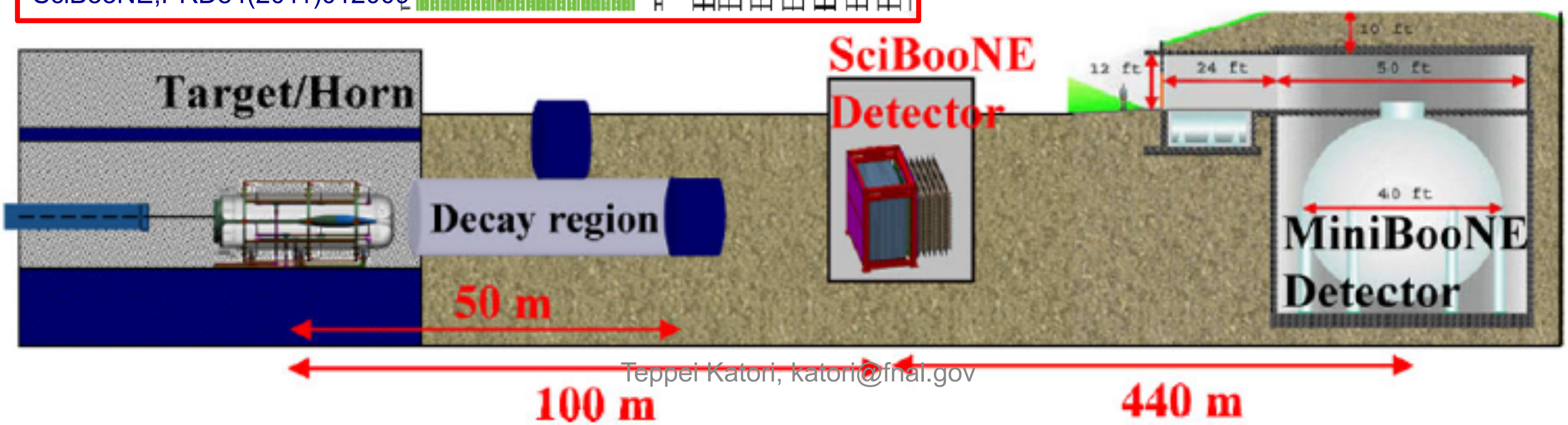
4. ν_e from K^+-decay constraint

SciBooNE is a scintillator tracker located on BNB (detector hall is used by ANNIE now)
- neutrinos from kaon decay tend to be higher energy, and tend to make 3 tracks
- from 3 track analysis, kaon decay neutrinos are constrained (0.85±0.11, prior is 40% error)





(c) 3-Track Sample



4. External γ constraint

All backgrounds are internally constrained
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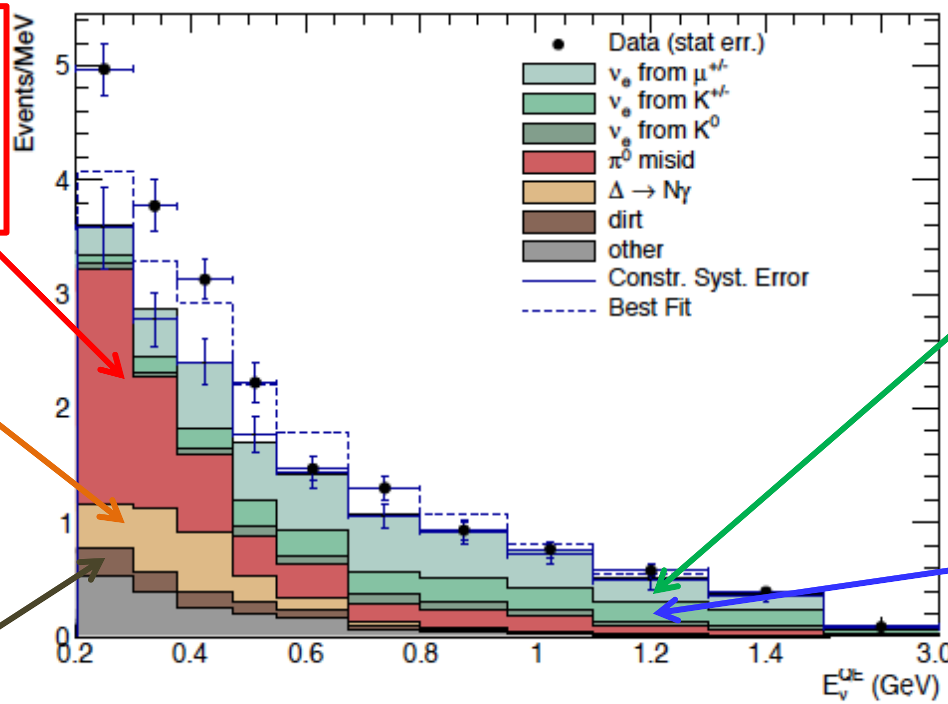
Asymmetric π^o decay is constrained from measured $CC\pi^o$ rate ($\pi^o \to \gamma$)

Δ resonance rate is constrained from measured $NC\pi^o$ rate

dirt rate is measured from dirt data sample



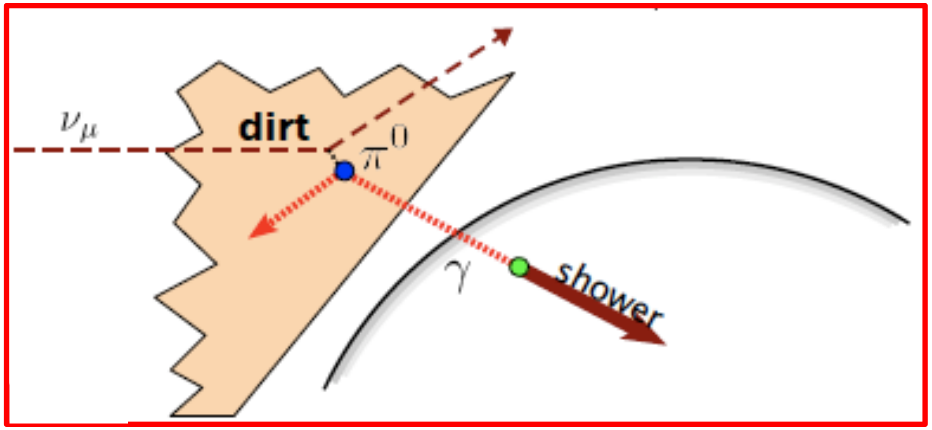
ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

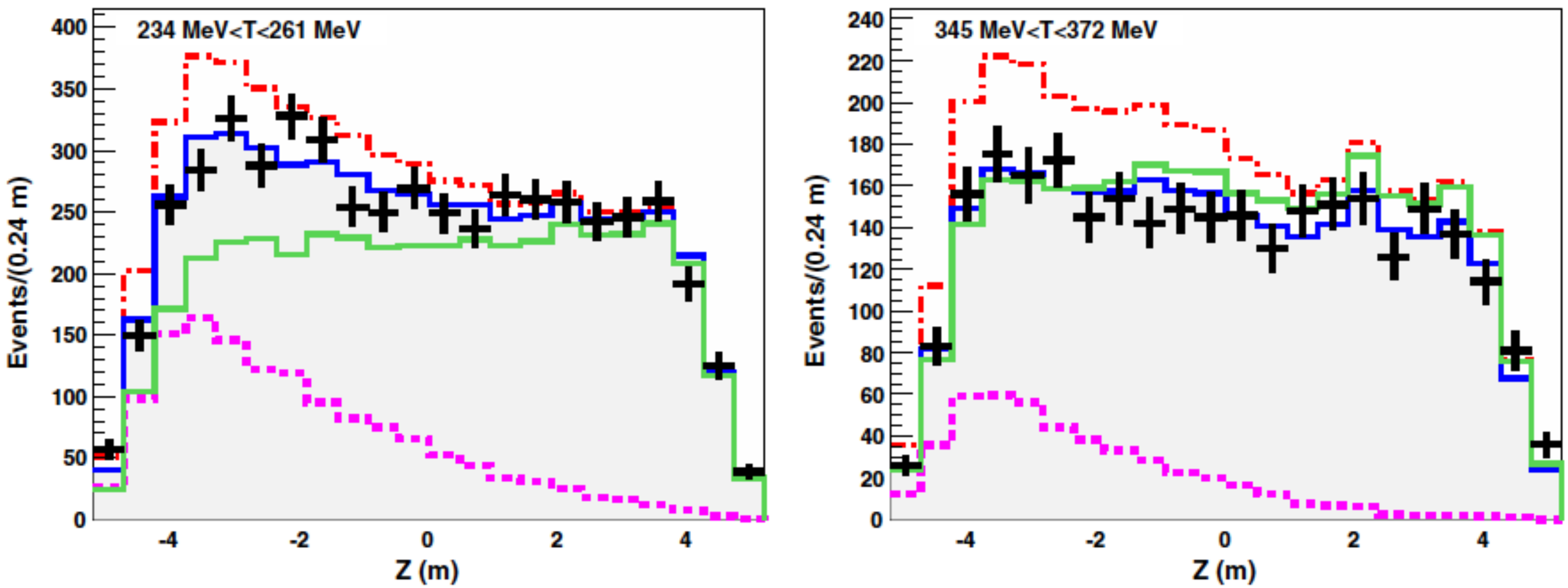
4. External γ constraint

MiniBooNE detector has a simple geometry
- Spherical Cherenkov detector
- Homogeneous, large active veto

We have number of internal measurement to understand distributions of external events.



e.g.) NC elastic candidates with function of Z
Mis-modelling of external background is visible



4. Internal background constraints

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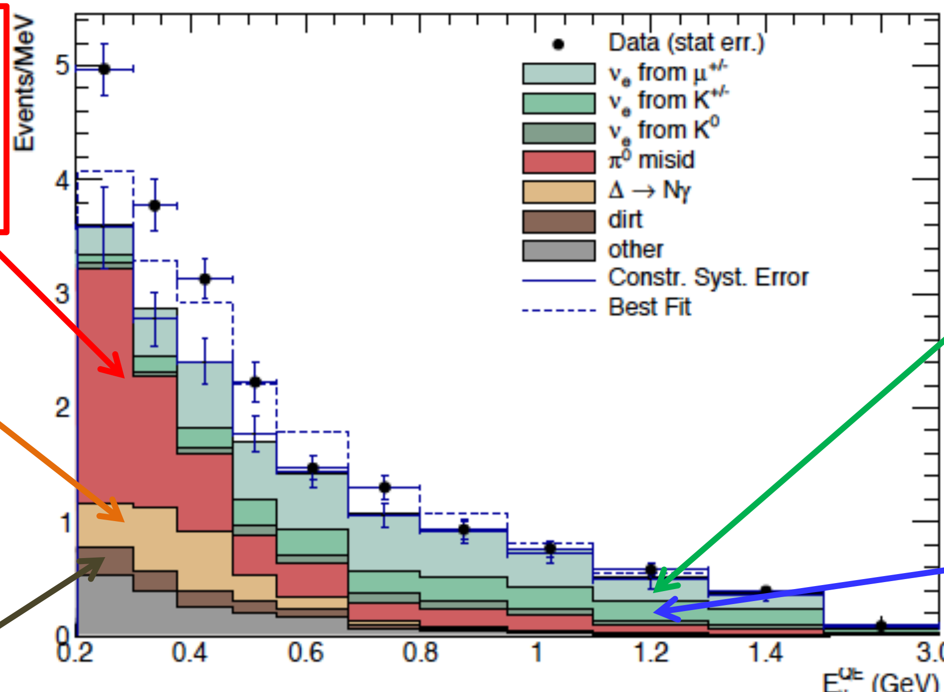

ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

Major backgrounds are all measured in other data sample and their errors are constrained!

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5. BSM neutrino oscillation model

Lorentz violation as alternative neutrino oscillation model

- Making a new texture in Hamiltonian to control oscillations.
- Could explain all signals, including LSND and MiniBooNE.
- This moment, no LV-motivated models can explain all signals.

LV-motivated effective Hamiltonian

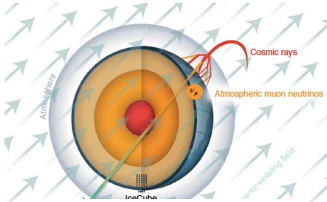
$$h_{\rm eff}^{\nu} = A\begin{pmatrix}1&1&1\\1&1&1\\1&1&1\end{pmatrix} + B\begin{pmatrix}1&1&1\\1&0&0\\1&0&0\end{pmatrix} + C\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix},$$

where $A(E) = m^2/2E$, $B(E) = \mathring{a}E^2$, and $C(E) = \mathring{c}E^5$

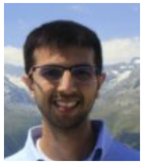
It is extremely difficult to make a neutrino oscillation model without neutrino mass, but consistent with all high-precision data.

Test of Lorentz violation with neutrinos

- Almost all neutrino experiments look for Lorentz violation.
- Current best limits of Lorentz violation by neutrinos;
  - CPT-odd (dimension-3) < 2.0×10^{-24} GeV
  - CPT-even (dimension-4) < 2.8×10^{-28}



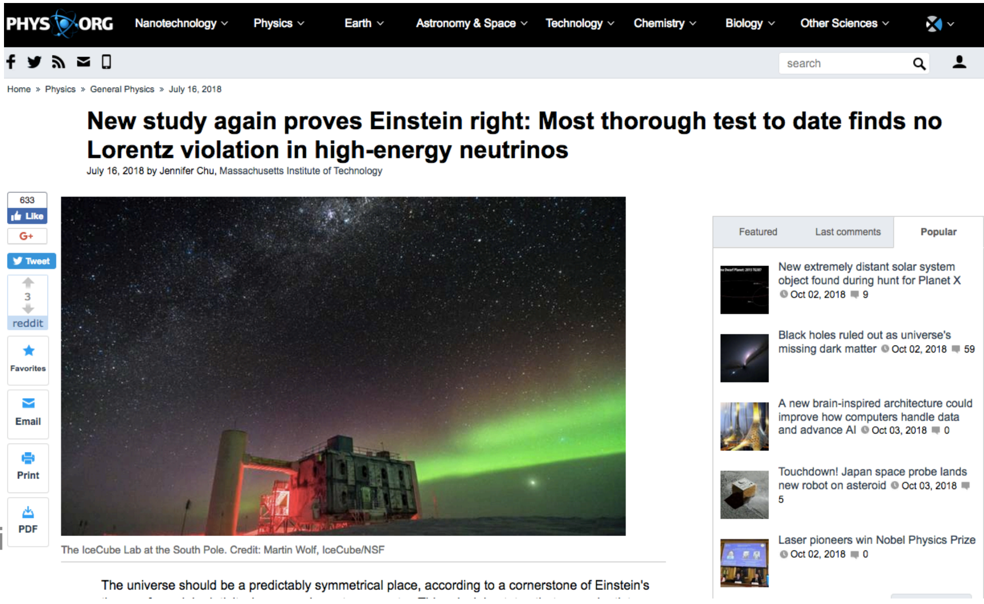
IceCube



Nature Physics 14(2018)961

Shivesh Mandalia (Queen Mary)

It turns out neutrino experiments are one of the highest-precision tests of space-time effects!



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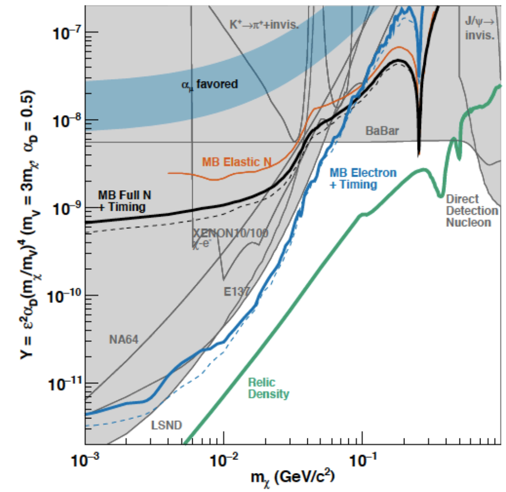
5. BSM electron scattering



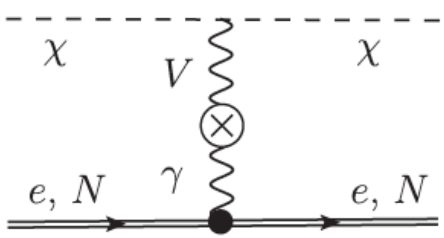
(a) vector portal

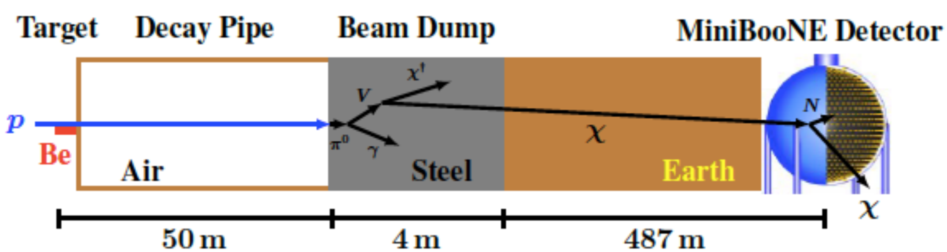
Dark matter particle - electron scattering

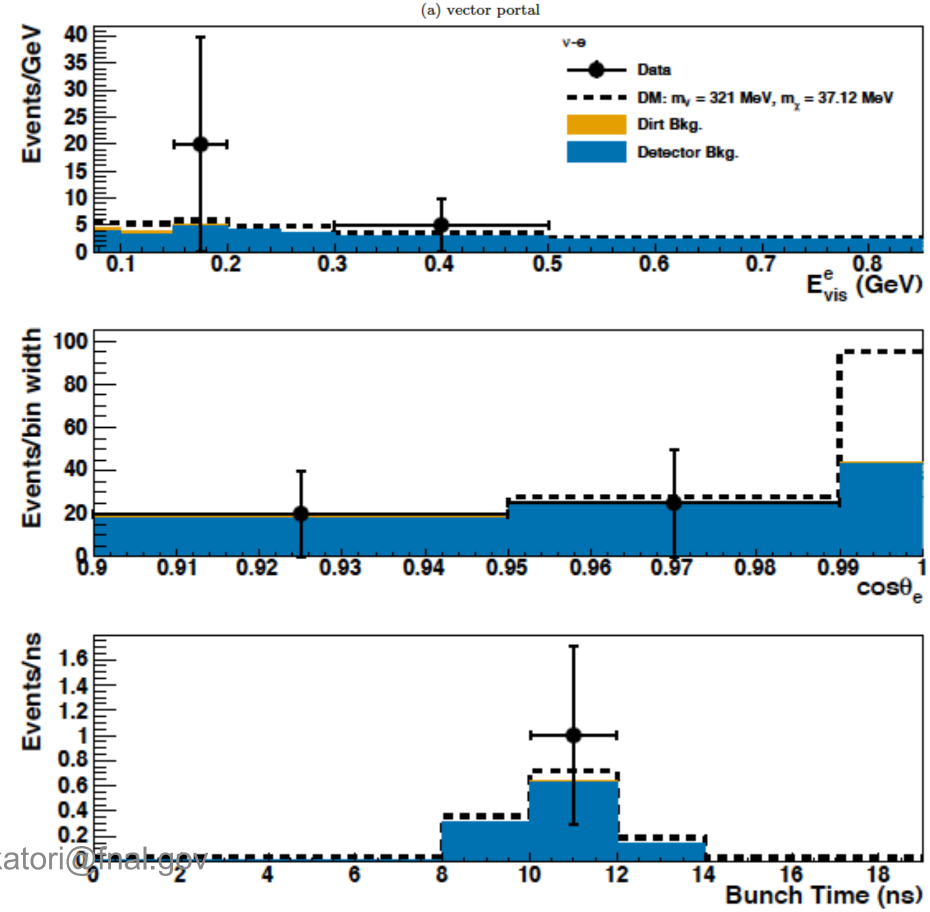
New particles created in the beam dump can scatter electrons in the detector.

However, MiniBooNE beam dump mode data shows no excess.

This result set limits on beam dump produced new particle – electron scattering interpretation.





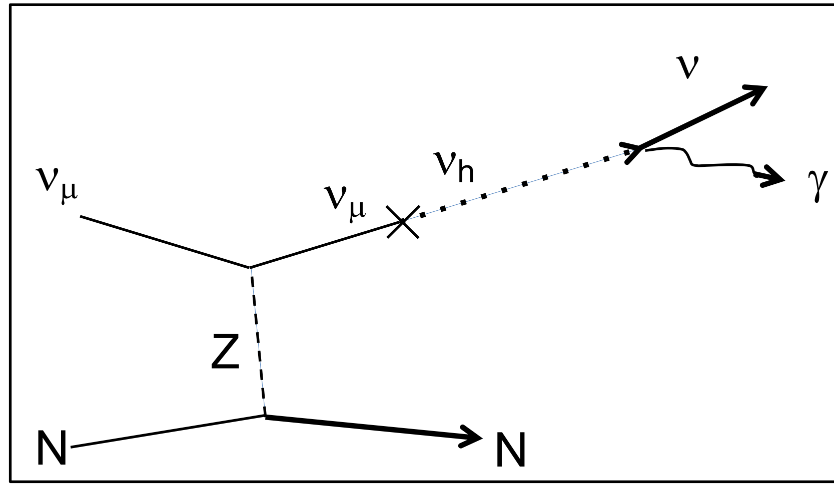


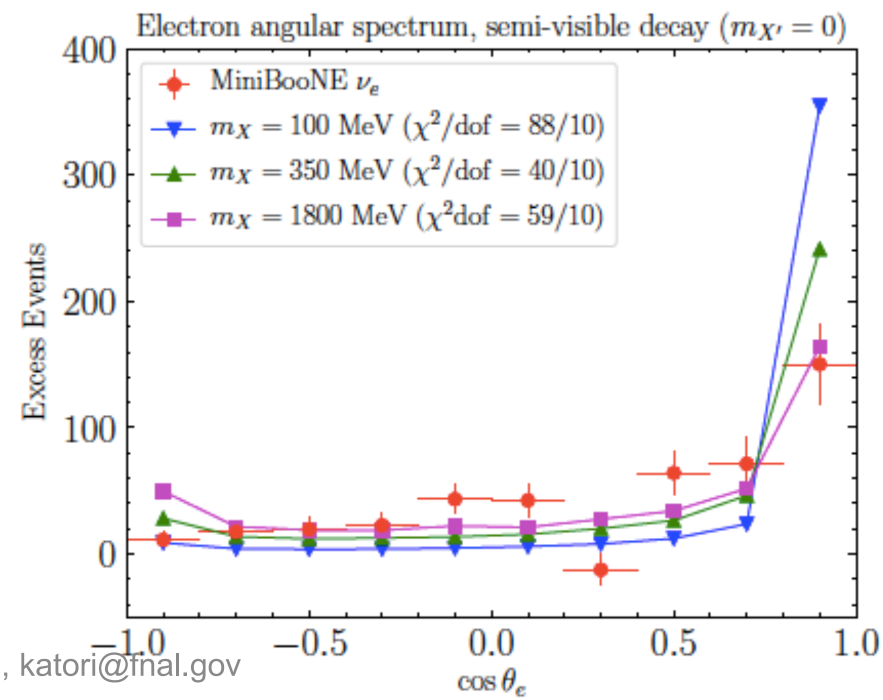
5. BSM photon production

Heavy neutrino decay γ production
- Minimum extension of the SM
- Heavy neutrinos are produced in the beamline by kinetically mix with SM neutrinos
- Heavy neutrinos decay to SM neutrinos in the detector.

These models have problems because they cannot reproduce the angular distribution of oscillation candidates.

heavy neutrino decay





Gninenko, PRL103(2009)241802 and many others, Jordan et al.,ArXiv:1810.07185
Ballett, et al, JHEP04(2017)102, Bertuzzo et al.,PRL121(2018)241801, Argüelles et al., ArXiv:1812.08768

5. BSM e+e- production

Heavy neutrino decay γ production

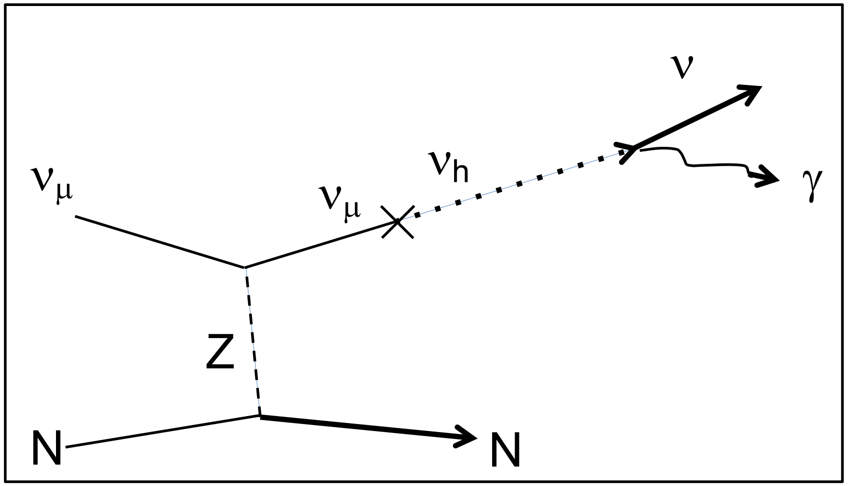
- Minimum extension of the SM
- Heavy neutrinos are produced in the beamline by kinetically mix with SM neutrinos
- Heavy neutrinos decay to SM neutrinos in the detector.

These models have problems because they cannot reproduce the angular distribution of oscillation candidates.

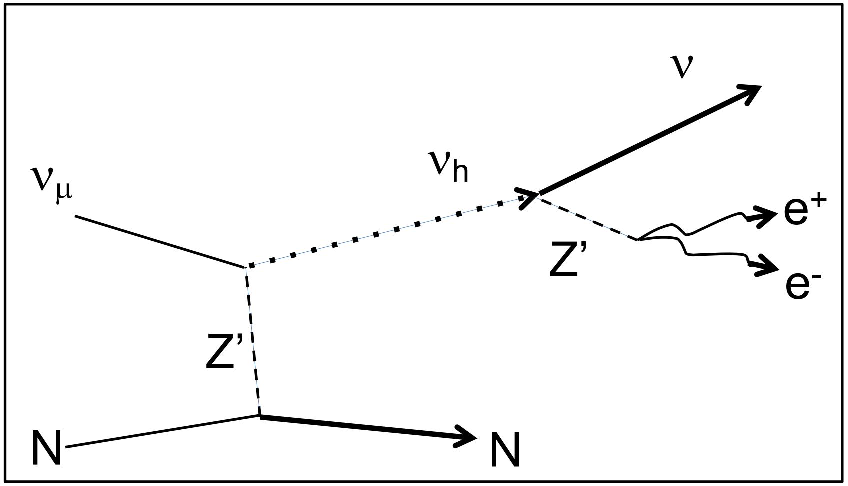
Z' decay model

A new class of models predict a heavy neutrino and a neutral heavy boson decaying to e+e-. These models explain both energy and angular distributions of MiniBooNE oscillation candidate data.

heavy neutrino decay



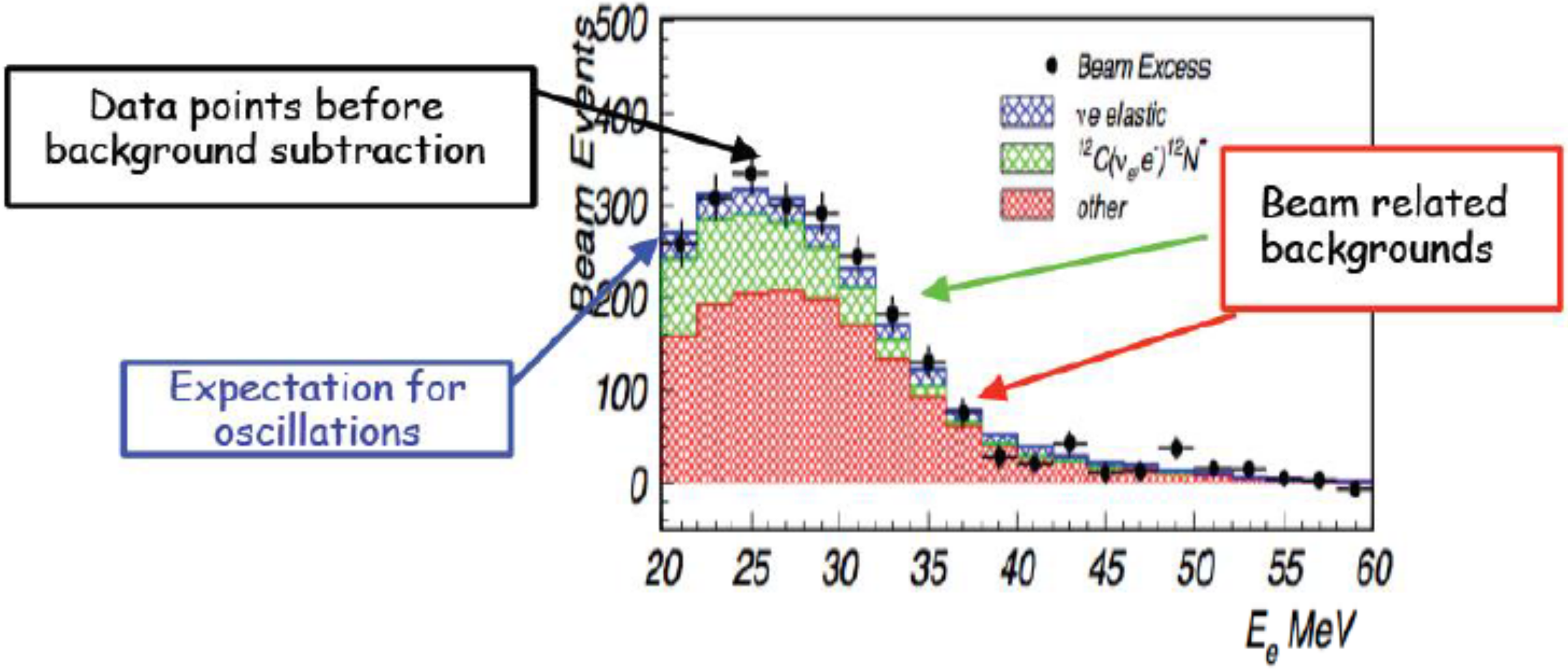
Z' decay



1. LSND experiment

LSND Starts it all...

Excess of events: 87.9 ± 22.4 ± 6.0



This is a tiny effect, and systematics will be crucial. It is a pity SBND is first!